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Agriculture Productivity in Tunisia Under Stressed Environment

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Agriculture Productivity in Tunisia Under Stressed Environment

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Preface

This volume came into conception to highlight the "**Agriculture Productivity in Tunisia Under Stressed Environment."** This unique volume is authored by the experts in the topic from Tunisia to present the results and findings of their research work and the related state of the art connected to the book title. The volume consists of five parts including the introduction and conclusion parts. The book is comprised of 15 chapters written by more than 30 authors. **Part I** is an "**Introduction to the Agriculture Productivity in Tunisia** where the editors present a general overview and highlight the technical elements of each chapter.

Part II of the volume is an "**Overview of Tunisian Sustainable Agriculture**" and contains seven chapters. The chapter titled "**Assessment of the Environmental Sustainability of Family Farming: the Case of Cereal Sector in Tunisia**" aims to evaluate the current situation and expectations for the future development of family farming in four different Tunisian provinces. While the chapter titled "**Sustainability and Plasticity of the Olive Tree Cultivation in Arid Conditions**", reviewed the existing genetic resources, the required environmental conditions, and the orchard management used in different olive-growing conditions. This review detailed some techniques used in Tunisia for a productive and sustainable olive cultivation in different conditions. Additionally, the chapter titled "**Tunisian Date Cultivars: Economic Aspect, Physicochemical Properties, Sensory characterization and Potential Valorization**" highlights the importance of date palm tree in Tunisia and shows the different virtues of this noble fruit as well as possible avenues for its valorization whether in an artisanal or even industrial way. Moreover, the chapter titled "**Ecological Distribution, Phytochemistry and Biological Properties of Rosa Species in Tunisia**" presents a review chapter describing the Rosa species discrimination based on their geographic repartition, edaphic preferences, bioclimatic situations, plant communities, phytochemical compositions, and biological activities. The authors reported that *Rosa* species exhibit several biological activities and their phytochemical richness were influenced by species and organs variation, extraction protocols, and environmental conditions. Furthermore, the chapter titled "**Natural Mediterranean Plant Products: a Sustainable Approach for Integrated Pests Management in**

Mediterranean Region" provides an overview of the diversity of secondary metabolites in Mediterranean plants and their multifarious biological functions in crop protection against pests. On the other hand, the chapter titled "**Invasive Alien Plants Management in Tunisia**" focuses on the biological invasion process and impacts of *Solanum elaeagnifolium* Cav. in Tunisia. The authors present the main components of an effective IAP management scheme and propose methods and tools that can be integrated into a national plan dedicated to the management of this weed. While the chapter titled "**Study of the Effect of the Biochar Amendment on the Physic-chemical Properties of A Soil Cultivated In Green Mint (*Mentha Viridis L.*)**" concludes that organic fertilization can be a solution to improve the quality of aromatic and medicinal plants and the quality of methanolic extract and at the same time serves to reduce the impact of chemical fertilization.

On the other hand, **Part III** is titled "**Sustainable Agriculture Water Management**" and contains four chapters. The chapter titled "**Assessing the Water Productivity of Durum Wheat in Tunisian Semi-Arid Conditions**" deals with water productivity of durum grown under semi-arid conditions. This chapter emphasizes a policy for maximizing yield which should be avoided under limited water resources conditions. Indeed, the water regime corresponding to maximum WUE does not correspond to maximum grain yield.

While the chapter titled "**Assessing Institutional Barriers to Effective Dissemination Strategies of Proven Water Management Practices to Face Climate Change Threats in the Citrus-Growing Area of Tunisia**" attempts to understand the current institutional barriers to effective dissemination of new irrigation technologies in the Citrus Cap Bon production area and the essential measures to be taken to overcome barriers with regard to the keys to better water resource management through surveying the involved institutions. In the chapter titled "**Water Isotopes for Sustainable Management of Agricultural Water: Case of the Plain of Mateur (North Tunisia),**" the authors applied a multicriteria approach in studying hydrodynamics of a multilayer aquifer system in Northern Tunisia, and they revealed that water chemistry is regulated primarily by the combination of three processes: (1) weathering of minerals such as silicates and calcites, (2) ion reverse exchange with host rocks, and (3) mixing with Cl-rich water from the Lake Ichkeul. The chapter titled "**Assessing the Blue and Green Water Resources Use for Regional Crop Production In a Semi-Arid Area (The Cap Bon Case Study, Tunisia)**" provides a quantitative analysis of the WF variation and a useful method to facilitate an integrated water resources management. They underline the development of irrigated agriculture, and significant improvements in blue WF induced a large pressure on water resources

Part IV titled "**Tunisian Marine and Terrestrial Living Environment**" is written in two. In chapter under the title "**Producing Barbarine Lambs on Tunisian Rangelands Could Be Sustainable and Provide Healthy Meat**," the authors present and analyze a data concerning growth performances, carcass traits, and meat fatty acid composition of lambs produced on different rangelands of the arid and semi-arid regions of Tunisia; they conclude that a better valorization of meat produced on rangeland could improve the economic viability and encourage farmers to maintain this system and to keep economic activity in poor rural areas.

While the chapter titled "**Freshwater Fish Farming In Tunisian Reservoirs: Diagnosis of The Current Situation, Fishery Management and Opportunities of Development"** describes the fish assemblage and the status of freshwater fish in Tunisian reservoirs by using multi-mesh gill nets in order to manage these fisheries and to develop this activity. The authors confirm that a poor diversity associated with an alarming decline in Tunisian stocks of autochthonous freshwater fishes was detected.

Part **V** is devoted to the last chapter in this book which is titled "**Updates, Conclusions and Recommendations for Agriculture Productivity in Tunisia Under Stressed Environment**" and is written by the editors. The chapter presents an update of the most recent findings, the most significant conclusions, and recommendations of the chapters contained in the volume.

The editors would like to deeply thank all the authors and reviewers who contributed to this volume; without their efforts and patience, it would not have been possible to produce this unique volume on **Agriculture Productivity in Tunisia Under Stressed Environment**. Also, thanks should be extended to include Springer team who largely supported the authors and editors during the production of this volume, particularly Andrey Kostianoy and Alexis Vizcaino.

Last but not least, editors welcome any comments, new chapters, and/or feedbacks to improve the next edition of the book. The contact information of the editors are presented in the first and last chapters of the book.

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Contents

Introduction to the Agriculture Productivity in Tunisia

Introduction to "Agriculture Productivity in Tunisia Under Stressed Environment"

Abdelazim M. Negm, Faiza Khebour Allouche, and Mohamed Abu-hashim

Abstract The main focus of this chapter is to present summaries of the chapters provided in the book "Agriculture Productivity Under Stressed Environment in Tunisia". The book consists of 15 chapters including the introduction and the conclusion chapters. The 13 chapters are presented under three themes, namely, Overview of Tunisian Sustainable Agriculture, Sustainable Agriculture Water Management and Tunisian Marine and Terrestrial Living Environment. A comprehensive state-of-the-art review and latest findings of research results are provided particularly for the main crops, olives, dates and cereals. Factors such as climate changes, pests, weeds and fertilizer applications that limit the agriculture production in Tunisia are discussed. Results of the studies related to face these limiting factors are presented. The marine and terrestrial living environment with special reference to the fishery developement and the importance of Tunisian rangelands systems are covered too.

Keywords Agriculture · Pest · Weed · Crop · Water · Fertilizer · Rangeland · Medicinal plant · Farming · Fishery · Management · Sustainability · Tunisia

1 Background

Although, Tunisia is known as Green country but due to the rapid growth of the populations, agricultural expansion and climate changes impacts, the agricultural environment is greatly affected and it becomes a necessity to address agricultural

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productivity under a stressed environment. Therefore, This book comes as a continuation of the previous efforts [1–4] to support the sustainability agenda in MENA regions. The follower book will be focusing on the MENA regions, [5].

2 Themes of the Book

Therefore, the book discusses in detail the following main themes, each in several chapters:

- Overview of Tunisian Sustainable Agriculture in seven chapters.
- Sustainable Agriculture Water Management in four chapters.
- Tunisian Marine and Terrestrial Living Environment in two chapters.

3 Chapters' Summary

The next subsections present briefly the main technical elements of each chapter under its related theme.

3.1 Overview of Tunisian Sustainable Agriculture

This theme is covered in 7 chapters. Chapter 2 is titled "**Assessment of The Environmental Sustainability of Family Farming: The Case of Cereal Sector in Tunisia**". The chapter is carried out within the project launched by the Food and Agriculture Organization (FAO) to evaluate the current situation and expectations for the future development of family farming in Tunisia. This initiative provided useful data to conduct the present study which aims to analyze the farmer-environment relationship through estimating the technical and environmental efficiency with which family farms operate. A literature review and the contribution of this work to previous literature are presented. Furthermore, this chapter offers an integrated farm sustainability assessment according to recent quantitative analytical approaches that recognize the stochastic conditions in which production takes place. The empirical study relies on a sample of farms specialized in cereal production in Tunisia. By measuring technical and environmental performance, the authors assess whether family farmers use their resources properly to reach their production objectives or not. Finally, farm management and policy implications are drawn along the chapter that is based on the obtained empirical findings. The authors indicated that family farming is the most common production system in Tunisia. It plays a key role in supporting sustainable farming practices through enhancing farmers' technical performance as well as contributing to the environmental sustainability of farms. Since celebrating the international year of family farming in 2014, the scientific community has produced several research studies that attempt to assess the role of family agriculture in rural development and providing sustainable food production.

Chapter 3 is titled “**Sustainability and Plasticity of The Olive Tree Cultivation in Arid Conditions**”. It presents a review of the existing genetic resources, the required environmental conditions and the orchard management used for productive and sustainable olive cultivation in different conditions. In Tunisia, the traditional cultivation method still remains the most frequent system used on extensive conditions despite the emergence of new intensive and irrigated modern olive growing methods. The Tunisian olive growing counts about 82 million olive trees covering 1 835 000 ha. In Tunisia, the traditional cultivation method remains the most frequent system used on extensive conditions despite the emergence of new intensive and irrigated modern olive growing methods. The major part of the olive orchards is conducted under rain-fed conditions (97% of the area). More than 80% of olive orchards are located in semi-arid and arid conditions (center and south), where the average of rainfall oscillated between 100–300 mm. However, efforts have been made in Tunisia, notably by increasing tree density and even by shifting from rain-fed to irrigated conditions to enhance the production and the profit of the growers. Moreover, the adoption of an appropriate technological package for each planting system (choice of variety, training system, pruning, irrigation, fertilization and pest control) is necessary.

Chapter 4 is titled “**Tunisian Date cultivars: Economic aspect, Physicochemical properties, sensory characterization and potential valorization**”. It shows the importance of dates in Tunisian culinary heritage and discusses the different physicochemical and sensory characteristics of the main Tunisian cultivars. Among fruit trees growing in southern Tunisia, date palm (Phoenix dactylifera L.) remains the most famous one, not only for its sweetness and chemical composition, but also for its possible valorisation in several fields such as food industries, cosmetics and agriculture. That’s why Phoenix dactylifera L. has an important place in the Tunisian national economy.

Many works have been done on the composition of Tunisian dates which confirm their nutritional richness. The results showed that the pulp of Tunisian date cultivars Deglet Nour, Khouet Kenta, Kentichi and Allig contain many benefits for the human body due to their richness in potassium, iron, vitamins, minerals, carbohydrates and antioxidant chemical groups. They are considered as energetic fruits and a key food source to facilitate the muscular effort.

However, fewer studies deal with sensory characterization. In fact, sensory analysis of dates is particularly difficult because of the sweet taste of the product. The authors’ studies on the organoleptic assessment, with its analytical and hedonic aspects, revealed that the Tunisian consumer is attracted by sweet cultivars with the best texture in the mouth and the best appearance.

Chapter 5 is devoted to “**Ecological Distribution, Phytochemistry and Biological Properties of Rosa Species in Tunisia**”. Rosa species is the main interest in this chapter. Rosa species are widely distributed in the Northern and Central of Tunisia. The investigation has concerned five Rosa species, among the eight ones described in the Tunisian flora. The presented review aims to describe the

Rosa species discrimination based on their geographic repartition, edaphic preferences, bioclimatic situations, associated species, phytochemical compositions and biological activities. Rosa species are belonging large the Section Caninae and are reported to have several preferences of climatic and edaphic conditions. For Synstylae species R. moschata is cultivated on sandy and equilibrate soils with semi-arid or subhumid climate (Zaghouan, nabeul, Bizerte and Testour regions). However, Rosa sempetvirens were disseminated in a large geographical area giving it the most elastic species. The floristic richness was more important in R. canina, R. sepmervirens and Rosa moschata associations as compared to those of Rosa agrestis and R. micrantha. These species are more resistant to arid climate when the rainfall is less than 400 mm.yr^{-1}. Finally, it was reported that Rosa species exhibit several biological activities and their phytochemical richness was influenced by species and organs variation, extraction protocols and environmental conditions.

Chapter 6 focuses on the title "**Natural Mediterranean Plants Products: A Sustainable Approach for Integrated Insect Pests Management**". It provides an overview of the diversity of secondary metabolites in Mediterranean plants and their multifarious biological functions in crops protection against pests and highlights that these metabolites can be used to protect our cultures against insect pests. This is important because the integration of plant products in pest management strategies would enhance sustainable agriculture and prevent loss in terms of both quality and quantity. The authors show that recent studies highlight their usefulness in plant defense against pathogens and insects' herbivores and their role in beneficial insects' attraction such as pollinators and auxiliaries. Also, they indicate that plant product are exploited for their benefit potential in crop protection due to their low toxicity to non-target organisms such as humans and auxiliaries, their effectiveness and environmental respect.

Chapter 7 is titled "**Invasive alien plants management in Tunisia".** It focuses on the management of *Solanum elaeagnifolium* Cav. Which is one of the most noxious invasive weed in many regions of the world. The authors present its status in the Middle East and North Africa countries and studied management actions undertaken in Tunisia to manage this species by applying different methods and tools.

The authors showed that managing invasive alien plants are urgent. The information presented in the chapter may lead to understanding invasions patterns and dynamics as a key to invasive alien plant management success by examining the controls over the different stages of the invasion process. Indeed, the invasions process has been divided into three major phases (introduction, establishment and invasion), each phase is linked to management priorities.

Chapter 8 is titled "**Study of the Effect Of Biochar Amendment On The Physic-chemical Properties of A Soil Cultivated In Green Mint (*Mentha viridis*L.)**". The authors show that the major challenge for the agricultural sector is to preserve and restore soils to ensure good food security for future generations. Therefore, they focus their discussions on how chemical fertilizers impact the environment, the soil and human health negatively and consequently, they indicate that organic manure is the best solution to fight these problems.

In recent decades, the focus has been on the adverse effects of the misuse of chemical fertilizers on soil health, human health and the environment. Mineral fertilization has caused groundwater pollution, soil sterilization. A decline in the profitability and quality of agricultural products is observed in addition to other impacts such as the contribution of the manufacture of fertilizers to the increase of the greenhouse and global warming. On the other side, good organic fertilization is essential for medicinal and aromatic plants that are used all over the world for therapeutic, food, cosmic, food, chemical, pharmaceutical, agri-food and industrial purposes.

3.2 Sustainable Agriculture Water Management

This theme is coved in chapters 9 to 12.

Chapter 9 highlight the methods of “**Assessing the Water Productivity of Durum Wheat in Tunisian Semi-arid Conditions**”. It focuses on Water Use Efficiency (WUE) of durum wheat grown under semi-arid conditions in Tunisia. The chapter is initiated by an assessment of irrigation efficiency and crop WUE of wheat in Tunisia. Then, long-term simulations are performed using a crop model in order to analyze the variability of crop WUE of durum wheat in relation to water supply and pedoclimatic variability. The model is calibrated and validated against the data collected from experiments conducted in different sites across Tunisia on durum wheat crop. After validation, the model is used to assess water productivity of durum wheat in the irrigated scheme of Bouficha for various water regimes applied to the crop and taking into account the variability of soil and climate conditions. The interrelationship between crop yield, water use and water use efficiency are determined to estimate optimum irrigation levels for efficient management of water resources for wheat production.

Chapter 10 focuses on “**Assessing Institutional Barriers to Effective Dissemination Strategies of Proven Water Management Practices to Face Climate Change Threats in the Citrus Growing Area in Tunisia**”. The authors show that weak linkages and the lack of accountability are revealed between research and extension institutions in Tunisia. Moreover, in the Mediterranean semi-arid context, water resources are shrinking and critical thresholds of water availability and quality and are threatening the sustainability of many agroecosystems. In the main production citrus area of Tunisia situated in Cap Bon peninsula and in the purpose of determining the institutional barriers for effective dissemination strategies of proven water management practices, qualitative data was collected through key informant interviews held with heads of institutions that are directly or indirectly related with the agricultural extension system in the studied area. The results are presented and discussed in the chapter.

The focus of Chapter 11 is on the title “**Water Isotopes for Sustainable Management of Agricultural Water: Case of the Plain of Mateur (North Tunisia)**”. These tracers are widely and extensively used in groundwater investigations to address problems related to recharge, delineation of flow systems and quantification of mass-balance relationships. In fact, isotope hydrology partially contributes to understanding the spatial and temporal variability of groundwater characteristics by providing information on type, origin and age of the water and therefore, the origin of water contamination sources. The stable isotope of the water molecule (18O and 2H) combined with classical hydrochemical tracers are efficient tools for evaluating hydrogeological processes and producing time and space-integrated knowledge of groundwater systems in particular in arid areas with short and lacking dataset.

Last decades, groundwater quality has become a worldwide priority because of the increasing exploitation, intensive farming and therefore water contamination by intensive use of fertilizers. The situation arisen has made it imperative to prevent and control water pollution and to have reliable information on water quality for its effective management.

Naturally occurring constitutive isotopes of the water molecules (18O, 2H, 3H) are considered as the best tracers of water history insight to aquifers. All these are discussed in this chapter.

This section ends by Chapter 12 which is devoted to discussing the issues related to the title "**Assessing the Blue and Green Water Resources Use for Regional Crop Production in a Semi Arid Area (the Cap Bon Case Study, Tunisia)**". The topic is very connected to the water footprint. Water footprint (how much water is used) and crop water productivity (how much productivity) are important indicators for evaluating the sustainability of agriculture water use under climate change. There is a need for a better assessment of green water of ecosystems and the socio-environmental issues associated with blue water development. Therefore, this chapter address the assessment of green and blue water footprints (WF) values for wheat, tomato and citrus crops. The authors considered the case of Cap Bon region northeastern Tunisia which has experienced changing policies for the management of water resources, and where the available data along the last decades allowed them to implement the WF quantification. Also, the main impacts of climate changes on agriculture and water resources and policies'/strategies' responses are presented. The methodology and the data requirements for WF implementation are also described. The main outcomes and discussion of the WF analysis are addressed.

3.3 Tunisian Marine and Terrestrial Living Environment

This last theme in the book is covered in two chapters.

Chapter 13 is titled "**Producing Barbarine Lambs on Tunisian Rangelands Could be Sustainable and Provide Healthy Meat**". The authors focus on how to promote the production of meat lambs on rangelands in the semi-arid regions, with giving a sign quality since the meat has a higher dietetic quality. However, rangelands should be improved to ensure the sustainability of the activity. A synthesis of data concerning growth performances, carcass traits and meat fatty acid composition of lambs produced on different rangelands of the arid and semi-arid regions of Tunisia was presented. Then, data concerned 87 male Barbarine post weaning lambs. These animals were used in four experimental trials comparing carcass traits and meat fatty acid composition between lambs reared on rangel and from the arid and the semi-arid region of Tunisia and lambs reared indoor with oat hay. For the two feeding systems, lambs were supplemented with concentrate (100 à 500 g/d), in order to maintain the same ADG between the groups of each trial. The rangelands belong to three sites of the Tunisian arid and semi-arid region (Sidi Bouzid Est; Menzel Bouzaine; Saouef and Zaghouan). The sustainability of this system was then discussed.

The title of chapter 14 is “**Freshwater Fish Farming in Tunisian Reservoirs: Diagnosis of the Current Situation, Fishery Management and Opportunities of Development**”. In this chapter, the authors describe the fish assemblage and the status of freshwater fish in Tunisian reservoirs by using multi-mesh gill nets in order to manage these fisheries. A total of 14 surveys were undertaken in the most important Tunisian reservoirs in order to monitor and to assess the state of Tunisian freshwater fisheries. Multi-Mesh gill nets designed for sampling fish in Bakbeka, Bir Mcherga, Bouheurtma, Bezirekh, Ghezela, Kasseb, Laabid, Lahjar, Mellegue, Mlaabi, Sidi Barrak, Sidi Saad, Sidi Salem and Seliana reservoir were used. Eight species were caught in the prospected reservoirs: Luciobarbus callensis, Mugil cephalus, Liza ramada, Sander lucioperca, Scardinius erythrophthalmus, Rutilus rutilus, Pseudophoxinus callensis and Cyprinus carpio. From the reservoir to the tributary, the fish biomass distribution is governed by the depth and it was abundant in the upper water layers. The results are presented and discussed in the chapter.

The book ends with chapter 15 which has a set of conclusions and recommendations in addition to an update to the literature from recent sources including [6–11].

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Overview of Tunisian Sustainable Agriculture

Assessment of the Environmental Sustainability of Family Farming: The Case of Cereal Sector in Tunisia

Bouali Guesmi, Ibtissem Taghouti, Hassen Abdelhafidh, Salah Selmi, and Lamia Arfa

Abstract Family farming (FF) plays a key role in local economies that contribute to meet Sustainable Development Goals (SDGs) worlwilde and especially in developing countries. Since 2014, the international agenda of the united nations has paid more attention to promote FF at the core of agricultural, environmental and social policies. Accordingly, many efforts at the national, regional and global levels have been made to support FF. In this context, it is so relevant to define tools that help monitor farmers' performance and assist in better targeting policy measures. The objective of this study is to assess to what extent Tunisian farms, specialized in cereals production, are technically and environmentally efficient. To do so, we use a methodological approach that integrates pollution considerations based on state contingent techniques. Our results indicate that technical efficiency of family farms is slightly lower in bad (59%) than in good (64%) growing conditions while environmental efficiency can be improved more under good (65%) than bad (70%) growing conditions.

Keywords Technical & environmental efficiency · Uncertainty modelling · State-contingent methods · Family farming · Tunisia

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1 Introduction

Negative externalities derived from intensive agricultural practices have led to raise social and political concerns about the sustainabilty of current farming systems. Recently, Agricultural policies agendas have continuously considered environmental impacts of agriculture. Many efforts have been made to support alternative farming systems that minimize pollution and enhance farmers' economic and environmental performance through using safer and more environmentally friendly methods.

Family farming has received substantial attention given its potential to contributre to achieve the sustainable development goals. In this context, the United Nations declared 2014 as the International Year of Family Farming (IYFF) that could help reduce poverty and improve food security. Family farming plays a key role in local economies that contribute to ensure environmental sustainability, efficiency and equitability. The aim of IYFF was to reshape family farming strategies to increase awareness and understanding of the challenges faced by smallholders and to adopt effective tools to support family farmers [1].

The majority of the world's agricultural land are managed by family farms which represents the backbone of food production sector [1]. It plays a key role in regard to socio-economic, environmental and cultural conditions of farmers, in particular in rural areas. Also, it represents the main social base for most developing countries which contributes almost 80% to global food production, 98% to food production in Sub-Saharan Africa and almost all cotton, cocoa and coffee production worldwide [1]. Moreover, it occupies around 40% of the total agricultural land in the world and becomes number one source of employment worldwide. Despite the relevant role of family farming in the world in general and in Tunisia in particular, the literature on efficiency performance of this farming type is certainly insignificant.

The cereal sector plays a relevant role in the Tunisian agricultural economy. However, this sector still suffers from many problems, particularly a high variation in production and yield which can lead to negative effects on the national economy. National agricultural reforms contribute to ensure an acceptable annual production and to improve rural livelihoods. Consistent with current agricultural policies, it is necessairy to choose robust and effective tools that help develop adequate policy measures. In spite of the relevance of the cereal sector in Tunisia, the literature on cereal farms' performance is very sparse, which may be mainly attributed to data availability. Recently, there have been a few attempts to examine technical and economic performances of cereal farms based on different approaches. Among these studies, the analyses on TE have gained special relevance. Parametric, specifically a Stochastic Frontier Analysis (SFA) method and non-parametric techniques, especially the Data Envelopment Analysis (DEA), have largely served this purpose.

Based on the SFA technique, Bachta and Chebil (2002) reported an inverse relationship between farm size and technical efficiency for a sample of grain farms in Sers (Kef region, Tunisia). The authors obtained mean TE levels of 0.81, 0.72 and 0.68 for small, medium and large-scale farms, respectively. Amor and Muller (2010) used the SFA to evaluate the TE ratings achieved by cereal growing farms located in different regions of Tunisia. They found a mean efficiency score of 77%. Dhehibi et al. (2012) showed a similar TE level for a sample of wheat farms in the governorate of Beja. Using nonparametric DEA model, Chebil et al. (2015) obtained lower TE level compared to previous finding indicating that irrigated wheat farmers in Chebika region (Central Tunisia) reach, on average, about 71% of their maximum potential output assuming constant returns to scale. In another DEA-based study, Abdelhafidh et al. [2] examined the technical performance of a sample of rainfed wheat production in the region of Zaghouan during the period 2015–2016. They found low mean technical efficiency scores on the order of 58%. In another recent study conducted by Chemak el al. (2018) concluded that the durum wheat production could be improved by 28% without changing the current technology process. More recently, Rached et al. [4], through SFA aproach, obtained higher mean technical efficiency levels of 0.85 humid region T-sample of cereal farmers located in the subunisia.

Knowledge about technical and environmental efficiency (TE and EE, respectively) with which family farms operate can provide relevant information for economic agnets who are interested in supporting both sustainable farming practices and the growth of cereal sector within Tunisia. Whereas high TE measures are a pre-requisite to ensure the economic viability of frams, high environmental performance is also required to attain sustainable development goals [5]. In the following lines, a literature review on EE is presented.

Conventional performance measures mainly deal with the efficient use of inputs and outputs. However, the assessment of environmental firm-performance has gained the special attention for economic research. This led many authors to include environmental concerns, and extend traditional efficiency measures to account for both technical and environmental dimensions [6–9]. The first group of studies assumes that pollution and production are complementary outputs showing positive correlation [10, 11]. The second line of research draws upon weak disposability assumption considering pollution as a bad output, that is mitigating environmental damage comes at the cost of reducing the amount of the good output [12, 13].

More recent studies have shown that previous approaches to environmental performance present some drawbacks which do not allow to address material balance concerns [14, 15]. To overcome these shortcomings, Coelli et al. [17] developed a new measure using the materials balance principle without introducing any additional an extra pollution variable in the production technology. Another alternative method to model pollution developed by Murty et al. (2012) introduces the notion of by-production which allows considering the interaction of several separate sub-technologies.

Recent literature on efficiency has dealt with the suitable techniques to derive TE and EE measures (see, [16], for an overview of environmental efficiency techniques). The methodological challenge is to appropriately define the stochastic nature of production. Serra et al. (2014) and Guesmi and Serra (2015) developed another innovative approaches based on Murty et al.'s (2012) proposal and Coelli et al.'s (2007) principle, respectively. The authors extend further both methods by incorporating the stochastic nature of production through the state-contingent techniques suggested by Chambers and Quiggin (1998, 2000). This technique overcomes the most relevant shortcomings associated with previous approaches without foregoing their advantages to model pollution. One attractive advantage of this method is that it recognizes that outputs are conditional upon states of nature and avoids yielding downward biased efficiency scores [18]. Despite the relevance of this approach in production economics, the empirical applications of the state-contingent technologies to the analysis of environmental assessment is still sparse. Our work contributes to filling this gap.

In contrast to previous studies on efficiency performance of Tunisian farms, our study focuses on estimating combined measures of TE and EE at the farm level. Serra et al.'s (2014) proposal, based on by-production principle, is used to derive TE and EE estimates. To achieve this objective, our analysis uses cross-sectional, farm-level data were obtained from a sample of 397 Tunisian farms that specialize in cereal production. To the best of our knowledge, our work constitutes the first study that assess combined TE and EE of cereal farmers in this country. By determining TE and EE of farms we can assess to what extent family farmers effectively use their resources to achieve their production objectives.

The remainder of the study is organized as follows. The next section will offer a general overview of the cereal sector in Tunisia. We then describe the methodology used in our empirical application. The data and the discussion of the main results from the empirical implementation are presented in the fourth and the fifth section, respectively. We finish the paper with concluding remarks.

2 Cereal Sector in Tunisia

The cereal production in Tunisia is of clear strategic importance in terms of economic, social and environmental development. In 2018, the cereal sector produced 1.4 million tonnes accounting for 8% of the total agricultural added value and contributed about 1% to the gross domestic product [19]. Also, it employs directly or indirectly about 50% of the labor force working in agriculture, that is more than 240,000 farmers are dedicated to this growth. Thus, this sector provides about 6.9 million working days per year which contributes to maintaining the population in rural areas. Furthermore, the cereal production grows at an annual rate of 6.5% during the period 2009–2018 which could reduce the gap in the trade balance of agricultural and food product.

The cereal area represents about one-third of the total utilized agricultural area (UAA) (1.16 million hectares), of which almost 73% are located in the northern region where the climatic and edaphic conditions are favorable to cereal growing [20]. Moreover, most of the water resources (77%) are concentrated in these areas of production. In 2018, about 46% (534 thousand hectares) of the Tunisian cereal area is devoted to durum wheat. Barley is the second most common grain production (45%), followed by soft wheat (7%) [19]. The cereal production is mainly concentrated in the north and central Tunisia generating 87% and 10% of total cereal produced in this country. The average annual production of the last 10 years is almost 1.7 million tonnes. During the last decade, the highest production level was achieved in 2009 with about 2.5 million tonnes while the lowest one (1.1 million tonnes) was in 2010 due to mainly water scarcity. Nevertheless, cereal productivity in this country is still very low compared to either world average (3.9 tonnes per hectare) or its potential with an average of 2 tonnes per hectare in 2018 [20, 21].

On the other hand, the cereal production and yield are highly dependent on climatic conditions, particularly rainfall with frequent droughts, given that the major farms rely on rainfed agriculture. The irrigated area occupies 61 thousand hectares representing only less than 5% of the cultivated area, however, it contributes 12.5% to total cereal production [19]. Many policies reforms have been made to improve the cereal yield through encouraging farmers to adopt certified and high yielding varieties, improving management practices, intensification and extension of the irrigated area and subsidizing the costs of production and inputs [22, 23]. It is important to evaluate the current situation and the future development of cereal sector in Tunisia. The relevant contribution of this sector to the agricultural economy makes this analysis interesting.

3 Methodological Framework

Recently, traditional TE measures have been extended to incorporate pollution considerations. Late developments in this literature have stressed out the need to consider the materials balance condition in order to provide reliable measures of farms' environmental performance. Serra et al. (2014), based on Murty et al.'s (2012) model, have slightly modified the by-production approach to account for material-balance concerns specific to agricultural technologies under the stochastic conditions of production (Fig. 1). The model specification relies on state-contingent techniques. The latter can be defined by differentiating outputs according to all possible states of nature.

The set of states of nature can be determined by $\Phi = \{1, 2, \ldots, S\}$. Following [24], we distinguish two types of variables namely, random variables and ex-post outcomes. The former are mainly intended and unintended outputs and defined as vectors in $\mathbb{R}^{\Phi}$.

Consider a firm that uses N nonpolluting inputs denoted by $x = (x_1, \ldots, x_n)' \in \mathbb{R}^N$ and K runoff generating inputs represented by $g = (g_1, \ldots, g_k)' \in \mathbb{R}^K$ those that generate runoff pollution, to produce M good outputs, $\tilde{y} = (\tilde{y}_1, \ldots, \tilde{y}_m)'$, and K unintended by-products,[1] $\tilde{z} = (\tilde{z}_1, \ldots, \tilde{z}_k)'$, generated by "polluting" inputs under states of nature s. the production technology can be defined as:

$$T = \{(x, g, \tilde{y}_1, \ldots, \tilde{y}_M, \tilde{z}_1, ..., \tilde{z}_k) : (x, g) \text{ can produce } (\tilde{y}_1, \ldots, \tilde{y}_M, \tilde{z}_1, \ldots, \tilde{z}_k)\} \quad (1)$$

[1] Since our sample farms are rain-fed, unintended outputs $\tilde{z}$ present major flexibility to be allocated across different states of nature given the possibility of environmental factors, beyond the farmer's control (e.g., rainfall), to determine which component of the fertilizers applied is fixed on the plant and which component migrates to the environment (Serra et al., 2014).

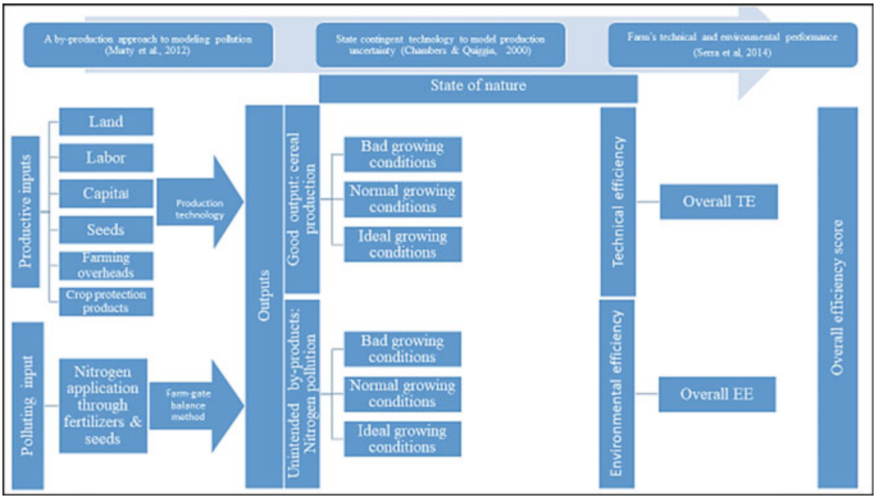

Fig. 1 Flowchart of methodological framework. *Source* own elaboration

Let $\tilde{p}_k$ represents the runoff inputs that are absorbed in the production of the intended outputs and it is determined based on a material-balance principle. It is computed as the difference between the runoff by products produced by the "polluting" inputs in each state of nature and the application of the runoff-producing inputs. The material-balance equation can be specified as:

$$p_{ks} = g - z_{ks} \tag{2}$$

Therefore, the new general specification for the productive technology is expressed by the following set

$$T^Y = \{(x, g, \tilde{y}_1, \ldots, \tilde{y}_M, \tilde{z}_1, \ldots, \tilde{z}_k) : (x, g_1 - \tilde{z}_1, \ldots, g_k - \tilde{z}_k) \text{ can produce } (\tilde{y}_1, \ldots, \tilde{y}_M)\} \tag{3}$$

Serra et al.'s (2014) proposal assumes that both productive inputs and runoff-producing input applications can affect the actual stochastic production of runoff levels. Thus, the second component of our specification is defined as follows:

$$T^Z = \{(x, g, \tilde{y}_1, \ldots, \tilde{y}_M, \tilde{z}_1, \ldots, \tilde{z}_k) : (x, g) \text{ can produce } (\tilde{z}_1, \ldots, \tilde{z}_k)\} \tag{4}$$

Following [15]'s assumption, a firm's technology can be composed of several sub-technologies. Indeed, the overall technology is the intersection of these two feasible production sets:

$$T = T^Y \cap T^Z \tag{5}$$

To estimate the technology set defined by Eq. (5) we used DEA techniques given their advantages over SFA approach. Mathematical programming is preferred to parametric frontier methods especially with the application of state-contingent techniques due to Multicollinearity issues which may conduct to misleading estimates [25, 26]. Our empirical application considers three possible states of nature: bad (s = 1), normal (s = 2) and ideal (s = 3) crop growing conditions. For a given set of observations on nonpolluting inputs, polluting inputs, ex-ante production and runoff levels $\left(x^i, g^i, \tilde{y}_1^i, \ldots, \tilde{y}_M^i, \tilde{z}_1^i, \ldots, \tilde{z}_k^i\right)$, $i = 1, 2, \ldots, I$ where I represents the number of farms, the sub technology T^Y is approximated, assuming constant returns to scale and free disposability of either inputs and outputs, by the following expression:

$$T^Y(I) = \left\{ \begin{array}{l} (x, g, \tilde{y}_1, \ldots, \tilde{y}_M, \tilde{z}_1, \ldots, \tilde{z}_k) : \\ x \geq \sum_i \varphi^i x^i, \\ g_k - \tilde{z}_k \geq \sum_i \varphi^i \left(g_k^i - \tilde{z}_k^i\right), \; k = 1, \ldots, K, \\ \sum_i \varphi^i \tilde{y}_m^i \; \geq \tilde{y}_m, \; m = 1, \ldots, M, \; \varphi \in \mathbb{R}_+^I \end{array} \right\} \tag{6}$$

While the second possibility production set T^Z holds free disposability assumption of non-polluting inputs, the production of $\tilde{z}_k$ is weakly disposable indicating that reducing pollution is not free. In other words, this assumption implies that mitigating pollution comes at the cost of decreasing the quantity of intended output. Hence, T^Z is specified as follows:

$$T^Z(I) = \left\{ \begin{array}{l} (x, g, \tilde{y}_1, \ldots, \tilde{y}_M, \tilde{z}_1, \ldots, \tilde{z}_k) : \\ g \leq \sum_i \mu^i g^i, \\ \tilde{z}_k \geq \sum_i \mu^i \tilde{z}_k^i, \; k = 1, \ldots, K, \\ x \geq \sum_i \mu^i x^i, \; \mu \in \mathbb{R}_+^I \end{array} \right\} \tag{7}$$

Following [15], the overall efficiency score can be derived from efficiency indexes for each of the sub-technologies:

$$E_R(x, g, \tilde{y}, \tilde{z}) = \frac{1}{2} \min_{\beta,\gamma} \left\{ \frac{\sum_j \beta_j}{\Phi} + \frac{\sum_j \gamma_j}{\Phi} | \langle x, g, \tilde{y} \oslash \beta, \tilde{z} \otimes \gamma \rangle \in T \right\} \tag{8}$$

where $y \oslash \beta = \left\langle y_1 / \beta_1, \ldots, y_\Omega / \beta_\Omega \right\rangle$ and $z \otimes \gamma = \left\langle z_1 / \gamma_1, \ldots, z_\Omega / \gamma_\Omega \right\rangle$. Under Murty et al.'s (2012) approach, TE $= \beta$ and EE $= \gamma$.

4 Data

Our analysis focuses on a sample of Tunisian cereal farms. Data were obtained from a questionnaire that was distributed among 397 agricultural holdings specialized in the production of cereals crops. Our sample farms are mainly concentrated in four different provinces (namely, Jendouba, Zaghouan, Siliana and Kairouan). In 2014, these four regions represented together 35% of the total cereal area and contributed around 40% to total cereal production in Tunisia (MAFWR, 2014). The survey was conducted during the planning season in 2014 and took place from March to May 2014.

Data were also gathered on farms' planned input use. Inputs include details on total hectares (ha) of land planted to cereal mainly, wheat, barley and oat. In addition, crop-specific inputs include the use of seeds, fertilizers and crop protection products measured in physical and monetary units. Farming overheads represent water, energy, fuels, lubricants and contract work expenses. Total labor, expressed in hours, is mainly composed of family labor. Further, capital input represents the replacement value of machinery, other equipment and buildings used in the production process and is defined in Tunisian Dinar (TND[2]). Furthermore, we collected data on ex-ante farm cereal production for three alternative states of nature, bad, normal and ideal growing conditions ($y = (y_1, y_2, y_3)$) that are expressed in (TND).

Gathering ex-ante output information is not an easy task due to subjective opinions of farmers regarding crop yield distribution, which can lead to serious biased responses. To overcome this problem, previous studies supported using point estimates of yields under bad, normal and ideal growing conditions, as the most practical approach to eliciting information on ex-ante yields. Yields under normal conditions over a long period are usually a reference. Hence, farmers can provide yield data under bad and ideal conditions.

Regarding the estimation of nitrogen pollution, Serra et al. (2014) proposed the use of the farm-gate balance method. The latter views the farm as a unit and considers the nutrients imported (through inputs such as fertilizers, seeds and feedstuffs) and the nutrients exported (crop nitrogen removal, meat nitrogen content, etc.). Limited to data availability, we consider only two input sources namely, nitrogen applied through chemical fertilizers and seeds. Chemical fertilizers used by our sample farms are mainly Diammonium phosphate (DAP) and Ammonium nitrate.[3] The nitrogen output source is mainly crop-nitrogen removal. Since the latter is highly influenced by yields, three possible nitrogen outputs were estimated contingent upon environmental conditions which result in three possible nitrogen balances, z_1, z_2 and z_3 measured in kilos. As noted above, nitrogen balance is defined as the difference between nitrogen application and removal estimates.

Table 1 provides summary statistics for the variables used in the empirical analysis. Our sample farmers mainly managed small holdings cultivating, on average, 4

[2] 1TND $\approx$ 0.40 US Dollar.

[3] The NPK rating of Diammonium phosphate (DAP) and Ammonium nitrate are 18–46-0 and 33–0-0, respectively.

Table 1 Summary statistics for the variables used in the analysis

Variable	Variable description	Mean	Standard deviation
y_1	Output under bad growing conditions (TND)	6284.89	8320.18
y_2	Output under normal growing conditions (TND)	8062.86	9884.53
y_3	Output under ideal growing conditions (TND)	9941.44	11,615.77
z_1	Nitrogen balance under bad growing conditions (kilograms)	751.42	1192.01
z_2	Nitrogen balance under normal growing conditions (kilograms)	694.04	1150.93
z_3	Nitrogen balance under ideal growing conditions (kilograms)	635.37	1110.81
g	Nitrogen application through fertilizers & seeds (kilograms)	927.05	1415.60
x_1	Land (hectares)	4.37	4.31
x_2	Labor (hours)	89.99	164.75
x_3	Capital (TND)	8245.51	15,413.97
x_4	Seeds (TND)	668.87	781.56
x_5	Farming overheads (TND)	840.85	982.33
x_6	Crop protection products (TND)	436.11	779.50

Source: Own calculations from survey data

hectares. Consistently with the national cereal farms' average, 59% of the cereal area is devoted to wheat, barley (38%) and oat (3%) production. Sample farms dedicate, on average, 90 h (of which 71% mainly represents unpaid family labor) to cereal production during the growing season.

Farmers' yield expectations depend on crop growing conditions. While under bad conditions cereal production is around 6 thousand TND per farm, average output under ideal conditions is on the order of 10 thousand TND. The value of cereal production under normal conditions is about 8 thousand TND. Our statistics reveal that the output standard deviation increase according to stochastic conditions of production, suggesting higher variability in output across farms as growing conditions improve. Sample farms' investments in machinery and buildings are on the order of 8 thousand TND. To avoid production lossess due to mainly pest infestations and diseases, farmers spent around 1048 TND annually on chemical inputs to improve crop immunity. Annual expenses in seeds and farming overheads are rather low compared to the use of pesticides, insecticides and herbicides, and on the order of 670 and 841 TND, respectively. The total quantity of nitrogen applied through fertilizers and seeds by our sample farms averages around 927 kg (Kg). Table 1 shows that average nitrogen balances per farm in our sample vary from 635 to 751 kg per year according to the realized state of nature.

5 Empirical Results and Discussion

Table 2 presents descriptive statistics for computed overall technical efficiency and its decomposition into technical and runoff by-product components in order to provide insights on whether sample farms are using their resources optimally to reach their production objectives. Overall efficiency averages around 64%. In contrast to previous findings, our results show higher efficiency levels for state-contingent outputs and lower state-contingent nitrogen pollution.

Results indicate that TE estimates are, on average, (0.61) suggesting that sample farms could use on average 39% fewer inputs without altering current output level. Previous researches, using alternative methods to assess case studies have derived different results. Our findings are within the range of existing estimates in the literature indicating a relatively close performance levels to those obtained from previous studies which offered more optimistic TE estimates [22, 23, 27]. Differences in TE estimates can be attributed to either the use of different approaches or the assessment of different production systems.

Moreover, EE scores indicate an important margin to reduce nitrogen runoff, keeping the current output levels unchanged. This would conduct to mitigate the negative impacts of fertilizers on the environment (contamination of surface and groundwater, loss biodiversity, etc.…). If sample farms were environmentally efficient, around 33% of the current use of polluting inputs would be avoided. In the presence of inefficiencies, a more rational input use can reduce pollution levels at no cost and without adopting pollution abatement technologies [28, 29].

Average output efficiency across states ranges from 59% in the bad state of nature to around 61% in the normal and 64% in ideal states of nature indicating a relatively marginal variation. Regarding unintended output efficiency, our results reveal that the average farm's efficiency in controlling pollution drops as growing conditions improve. The nitrogen efficiency score in the ideal state of nature is 65% while it achieves 70% in the worst production scenario. Compatible with previous staudies,

Table 2 Summary statistics for technical and environmental efficiency estimates

Variable	Efficiency measures			
	Overall mean	State of nature		
		Ideal	Normal	Bad
Output	0.61 (0.29)	0.64 (0.27)	0.61 (0.29)	0.59 (0.33)
N-pollution	0.67 (0.31)	0.65 (0.34)	0.67 (0.32)	0.70 (0.32)
Overall	0.64 (0.26)	-	-	-

Note: The overall efficiency score corresponds to Eq. (8). The intended output and N-pollution efficiencies are derived from Eqs. (6) and (7), respectively. Standard deviation in parenthesis.
Source: Own calculations from survey data

TE efficiency increases slightly from bad to idea state of nature, while nitrogen efficiency suggests the opposite.

In order to provide policy conclusions based on our research findings, we recommend an adequate distribution of subsidies that target the farms who exhibit higher technical or environmental efficiency performance. Such incentives may encourage farmers to become more efficient technically (to ensure stronger economic sustainability) and environmentally (to ensure environmental sustainability). Compliance with a series of rules on good agricultural practices and environmental conditions require more control and monitoring. Farmers will be more motivated to comply with environmental standards, which may lead to the reduction of the quantity of unintended pollution derived from farming activities [30]. This reform would have strong implications for family farms in general and in particular for the cereal sector in Tunisia.

Further, farmers' performance improvement over time would help cereal farms to be more competitive in the market. Since family farms mainly use unpaid labor, they are likely to show poorer performance. Family labor often tend to be overused given its opportunity cost [31–34]. Indeed, improving efficiency performance could be achieved through information campaigns, education and training actions and extension services. Increasing farm size to improve the cereal production is not straightforward due to land market rigidities and limited cultivated area. Hence, a strategy based on efficient use of scarce resources as well as "polluting" inputs is especially relevant in the cereal sector. Improving the performance of decision-making units becomes a serious concern for policy makers to enhance cereal productivity, which in turn reduces the large deficit between domestic needs and production and ensures food security.

6 Concluding Remarks

Despite the relevance of the cereal sector in the Tunisian economy, there is no study that focuses on the environmental performance of cereal farms in this country. Ours contributes to filling this gap. The present study uses recent efficiency techniques to estimate firm-level sustainability indicators based on technical and environmental measures. This new approach, assuming that a firm's technology is composed by different sub-technologies, an intended-output and a residual-generation technology, [14, 15, 35], is adapted to accommodate the stochastic nature of production in which production takes place based on state-contingent methods [36].

Our empirical application relies upon a sample of Tunisian farms specialized in cereal production. To determine the environmental performance of farms, we use only two input sources namely, nitrogen applied through chemical fertilizers and seeds. Output technical efficiencies are on average 61%, while nitrogen runoff efficiency indices suggest substantial scope for reduction of nitrogen pollution, with an efficiency of 67%. Consistent with previous research, nitrogen inefficiencies increases from ideal to bad states of nature while intended output efficiency ratings suggest the opposite.

High-efficiency levels contribute to enhance the firm's economic and environmental sustainability. This could be achieved through the adoption of actions at different levels: farm, policy and academic levels. Academically, further research could help identify additional pollution sources, which may allow obtaining more reliable information on efficiency estimates.

Our results allow deriving some important policy implications and recommendations. Since there is considerable room to improve both technical and environmental efficiency, providing farmers with necessary information and training courses on how to appropriately apply chemical inputs could improve their production performance [31]. More rational and less arbitrary use of chemical inputs would certainly reduce pollution and improve technical performance. This can be achieved through specialized extension and training services that transfer knowledge to farmers.

Additionally, promoting sustainable economic practices becomes a topical issue for policy makers to enhance family farming performance and competitiveness. Public policies would support farmers that are concerned about fertilizer use and soil runoff to adopt friendly practices and invest in new technologies. Consistently, more accessible solutions and tools to control pests (e.g., precision agriculture, using information about soil nutrients, moisture and productivity of the previous year, resistant varieties) make framers more sustainable and help reduce environmental pressures. In this context, financial aid received by farmers could be redistributed based on farm technical and environmental performance. Furthermore, such subsidy scheme could be used as an effective tool to ensure viability of family farming in Tunisia. Finally, more collaborative interaction between farms and local services and administration could be a key tool for designing initiatives and policy programs aimed at improving farms' performance.

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Sustainability and Plasticity of the Olive Tree Cultivation in Arid Conditions

Mouna Aïachi Mezghani, Ibtissem Laaribi, Imen Zouari, and Amel Mguidich

Abstract The olive tree is the major cultural crop in many countries around the Mediterranean Sea. The olive orchards have been established in very different climatic conditions from arid condition (Southern Mediterranean) to more humid conditions (Northern one) and even in poor soil conditions with low organic matter. The tolerance of the olive tree to drought, its salt tolerant character and its major role both in minimizing erosion and desertification effects, have as result that the olive cultivation is the main crop able to establish a sustainable system in subsistence agricultural areas. The Tunisian olive growing counts about 82 millions of olive trees covering 1 835 000 ha. The major part of the olive orchards are conducted under rain-fed conditions (97% of the area). More than 80% of olive orchards are located in semi-arid and arid conditions (center and south), where the average of rainfall oscillated between 100–300 mm and showed low yield. The traditional cultivation method still remains the most frequent system used on extensive conditions. So, the main objective of the grower is to obtain higher productivity at the minimum cost and to produce olive oil with added value. Efforts have been doing in Tunisia, notably by increasing tree density and even by shifting from rain-fed to irrigated conditions. Nowadays, the adoption of an appropriate technological package for each planting system (choice of variety, training system, pruning, irrigation, fertilization and pest control) is necessary to enhance the production and the profit of the grower. This work is a review of the existing genetic resources, the required environmental conditions and the orchard management used in different olive growing conditions.

Keywords Sustainability · Variety · Soil management · Irrigation · Fertilization · Pest control · Tunisia

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1 History Overview

The domestication of the olive tree would have originated, like that of most fruit species, in the Near East or probably Asia Minor [1]. Recent studies show that the first wild traces of the olive tree were found in Asia Minor reinforcing the previous hypothesis. The olive tree dates back more than 14.000 years BC. Excavations at prehistoric sites have resulted in the discovery of fossilized leaves dating from the Paleolithic or Neolithic period, as well as traces of coal and pollen along the Sahara dating back some 12,000 BC [2]. The place where man began to cultivate the olive tree would be made in Syria, about 3500 BC [2].

The powerful civilizations of the eastern Mediterranean, such as those of the Phoenicians, the Greeks and then the Romans, disseminated this culture throughout the Mediterranean basin. Thus the olive tree extends in Italy, in France more precisely in Provence through the intermediary of the Phocaeans. On the southern coasts of the Mediterranean, the olive tree progresses through the Phoenicians, who introduce it into their colonies. The Phoenicians travel the Mediterranean by promoting this culture. With the period of great discoveries and then colonization, the olive tree crossed even the Atlantic and extended to more "exotic" countries such as California, Mexico, Chile, South Africa, China and Australia [3, 4].

Now, the olive tree is grown in all regions of the globe between latitudes 30 and 45 of the two hemispheres, from America (California, Mexico, Brazil, Argentina and Chile), Australia and China to Japan and South Africa. Despite this vast extension of the olive tree cultivation, the Mediterranean basin has remained its favorite soil, with almost 95% of the world's olive groves. Spain, Italy, and Greece of the European continent, Tunisia and Morocco of the African continent and Turkey and Syria of the Asian continent are the main olive-growing countries in the Mediterranean region [5, 6].

The olive tree, rich in its history in the region of the Mediterranean basin, was brought from the Middle East to Tunisia by the Phoenicians, founders of Carthage. The Carthaginians began planting the olive tree all over Tunisia, beginning with the island of Cyraunis (Kerkena), passing through Byzacène (Cap Bon), and more particularly Hadrumète (Sousse), and finally to the steppes of Kasserine and the south around Zarzis and the island of Djerba [7].

In the days of the Carthaginians, a real culture of the olive tree had begun to spread thanks to the advantages granted to the peasants who created olive groves. The decisive think of the enrichment of Hadrumetum is the cultivation of the olive tree which, from the end of the first century, supplanted that of cereals in Byzacene [8]. Then, the Romans developed it further by intensifying irrigation on this land where rain was scarce and inventing the technique of extracting oil as evidenced by the excavations of Sbeitla and El Jem as well as the numerous mosaics Roman discoveries in Sousse [7].

Then, the Arabs (Aghlabits, Fatimids, and Sanhajis) contributed to the spreading of the culture and the creation of commercial center particularly around Kairouan city. In the nineteenth century, the Beys encourage the plantation of the olive tree. After, the

French colonists, during the colonization period, contributed largely to the extension of olive tree plantations with the help of Tunisian cultivators in consideration of agreement called Mogharsa [9]. The remarkable extension of the olive cultivation during the last century placed the olive growing among the strategic sectors which plays an important socio-economic and environmental role.

2 Importance of the Olive Sector

In North African countries, olive cultivation is a crop capable of establishing a sustainable system in subsistence agricultural areas. The olive specie popularity is not only agronomic and economic but also related to the environmental and human health. So, the olive orchards have been established in very different climate conditions from arid condition (Southern Mediterranean) to more humid conditions (Northern one) and even in poor soil conditions with the low organic matter. Its tolerance of the olive tree to drought, its salt tolerant character and its major role both to reduce erosion and desertification, lead to the fact that the olive cultivation is a crop able to establish a sustainable system in subsistence agricultural area. The world's olive tree area is estimated at 11 240 556 hectares planted, or 1.5 billion trees, or an average of 130 trees per hectare. More than 31 million people around the world live mainly or incidentally from olive trees [10].

In Tunisia, in addition to its historical past and its civilization role, the olive tree plays a socio-economic role of paramount importance and occupies a place of choice both ecologically and agriculturally. Olive-growing comprises nearly 309,000 producers, or 60% of all farmers, who derive all or part of their income from the cultivation of the olive tree. Thus, Tunisian olive growing is one of the main strategic sectors of the economy in general and of agriculture in particular. The traditional cultivation methods exist even despite the emergence of the intensive and irrigated modern olive growing methods.

2.1 Cultivated Area, Tree Number and Varieties

Tunisia has the second largest olive-growing area in the world after Spain. Tunisia cultivates its olive trees on 1,825,000 ha or 16% of the world's olive-growing area. More than 97% of Tunisian olive groves are destined for production for oil extraction, the rest being reserved for table olive confectionery [7]. Olive trees are spreading all over the country from North to South under different bioclimatic conditions (Table 1). They cover the most diverse aspects: in association with other crops, cereals, fruit trees (North and Cap Bon) or in strict monoculture (Sahel and Sfax). They form, also, veritable green cords in the ravines and in the confines of the desert regions of the extreme south of the country. Private farms provide most of the olive production and are mostly small and family-type. Farms smaller than 20 hectares account for more

Table 1 Distribution of olive-growing areas in Tunisia [11]

Regions	Area(Ha)	Percentage(%)	Tree number(×1000)	Percentage(%)
North	277.000	15	30.272	36
East center	297.000	16	13.152	16
West center	528.000	29	19.919	24
Sfax	351.000	19	7.567	9
South	382.000	21	13.515	15
Total	1.835.000	100,0	82.425	100,0

than half of the olive-growing areas planted with olive trees and 83% of the total. Farms with a size of over 20 hectares (20 to 50 ha) hold 75% of the olive-growing land but are in the minority in terms of numbers.

The pyramid of the ages of the Tunisian olive tree currently highlights 3 1% of young olive trees (1 to 5 years), 54% of the olive tree in production (20 to 70 years) and 15% of old olive trees (over 70 years old). The used density varied according the climatic zone and the availability of water and the soil type. Three densities are recognised (a) 100 trees/ha in the north where he rainfall 400 to 600 mm, (b) 50–60 trees/ha in the center where the rainfall is 300 to 350 mm and (c) 17–20 trees/ha where the rainfall is 200 to 250 mm.

2.2 Production

The average production of Tunisian olive oil is over the last 10 years (2010–2019), was equal to 176 000 tonnes with a minimum of 70 000 tonnes and a maximum of 380 000 tonnes recorded during the 2013/2014 and 2018/2019 marketing years respectively. This level of production preserving Tunisia its second rang after the European Union. Important fluctuations can be seen from year to year due to the rain-fed conditions (aridity and low precipitations), the soil characteristics, the presence of old trees in traditional olive groves and even to the alternate bearing of the olive tree [7, 12].

Most oil production is provided by the cultivars ‘Chemlali’ and ‘Chétoui’ which are covering together more than 80% of the olive cultivated area (Fig. 1). It is important to mention that most traditional olive orchards (97%) are grown under rain-fed conditions and receive annually no more than 350 mm of rainfall in the north, less than 250 mm in the center and less than 100 mm in the Tunisian south [7, 13]. More than 70% of total number of olive trees is located in semi arid and arid regions (centre and south). The average yield per ha is about 800 kg/ha in the north despite the favourable conditions, 500 to 800 kg/ha in the center, and 200–300 kg/ha in the south with a national average of 400–500 kg/ha. This low productivity constitutes a real constraint for the improvement of the olive growing in Tunisia [9].

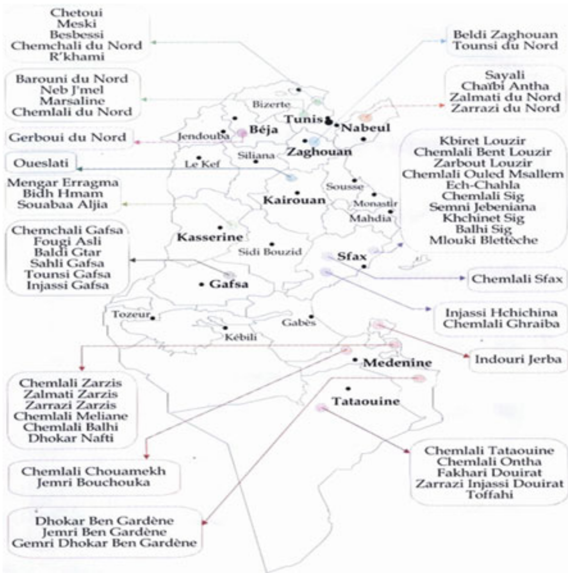

Fig. 1 List of varieties cultivated in Tunisia [26]

3 Genetic Resources

The genetic diversity could be an important source for the development of modern olive growing towards typical oil production. In fact, the modern olive oil industry requires new and more reproductive cultivars to sustain the new trends in olive growing. Therefore, there have been efforts for cataloguing olive cultivars in olive producing countries. The identification of olive cultivars has been traditionally carried out by morphological descriptors. With the development of chromatographic and spectroscopic methods, precisely in the 1990s, the identification of olive varieties based on the biochemical characteristics of their oils was used. Besides, in the last years, different molecular markers (RAPD, AFLP, ISSR, SSR, SNP) have been developed and applied for studying the variability of olive cultivars and their origin, providing a more powerful tool to guarantee varietal identification The best taxonomic results were achieved by combining morphological, biochemical and molecular markers [14–18].

The number of olive varieties grown in the world is controversial [3, 19, 20]. It counts 1275 varieties, recorded in the world, cultivated in 54 countries and preserved in 100 collections as mentioned by the olive tree germplasm database [21]. The actual number of olive varieties may be larger than previously published figures due to lack of information on several cultivars and ecotypes restricted to certain [16, 22, 23].

The investigation of the germoplasm resources in Tunisia has promoted to increase knowledge of the genetic patrimony and to insure its identification, conservation, evaluation, selection and finally genetic improvement [22]. Identification and characterization of Tunisian olive cultivars was developed by morphological [24–26] and molecular markers such as AFLP [27], RAPD [28], SSR [15, 29] and SNP [30].

In Tunisia, the first inventory of the main olive varieties was carried out [24]. This study reported the morphological and agronomical characterization of 15 local varieties 'Chétoui', 'Meski', 'Besbessi', 'Marsaline', 'Roumi', 'Gerboui', 'Oueslati', 'Chemchali', 'Chemlali', 'Beldi', 'Tounsi', 'Fouji', 'Rakhami', 'Sayali' and 'Barouni', and 3 introduced varieties; 'Manzanilla', 'Picholine' and 'Lucques'. Characterization of these varieties was based on morphological characteristics reported [31, 32]. The second inventory of autochtonous varieties and local types was established [26]. The authors illustrate 56 local olive varieties and types (Fig. 1). The identified olive varieties, in the second inventory, was characterized on the basis of the morphological characteristics of the International Olive Oil Council standard [4] and propagated and conserved in a germplasm bank in Boughrara-Sfax in central Tunisia (34°N, 21°E). A high number of local cultivars are also present but only in small areas due mainly to the used propagation methods. A multitude of autochthonous and local cultivars preserved in situ by olive farmers, but as yet unknown to nurserymen [22].

The two main oil varieties dominant in the olive plantations were 'Chemlali' in the centre and south and recover about 56% of the total area in dry conditions and 'Chétoui' in the north and recover about 12% of the total one in wet condition [26]. These two main varieties, alone, provide about 90% of the national olive oil production. The limited dispersion of other cultivars increases the relative importance of the 'Chemlali' denomination, which includes different vigorous and small-fruited genotypes, is therefore considered as a variety-population (Fig. 2). Its significant geographic extension and its persistence are due to its adaptation to arid conditions (two-third of plantations).

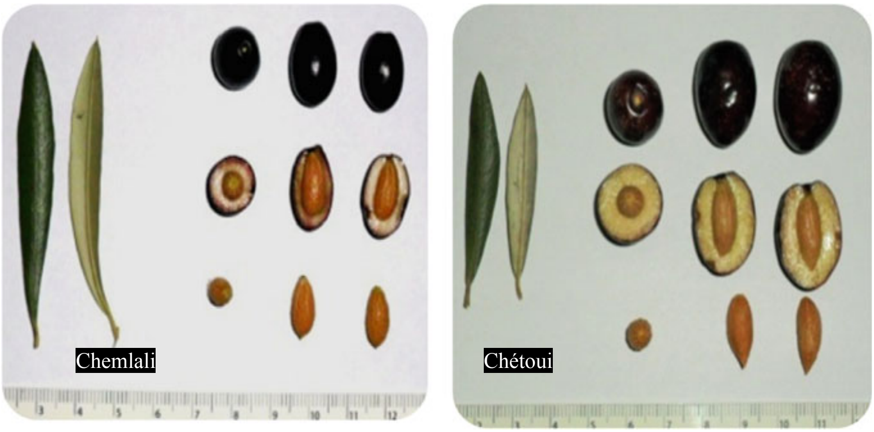

Fig. 2 The main important oil variety cultivated in Tunisia (Personal photos)

Studying the genetic diversity of the olive tree in the Sahel region of Tunisia, a prospecting effort was carried out in many ancient and historical olive groves of Sousse, Monastir, and Mahdia. One hundred forty five olive accessions were selected for their interesting agronomic attributes and their particular morphological characteristics. The physicochemical characterization of the oil extracted from repaired olive accessions allowed selecting those presenting an interesting oil quality with a high oleic acid content and low palmitic and linolenic acid content and also rich on tocopherols and polyphenols (antioxidants). Those accessions presented an interesting oil composition compared to classic oil variety 'Chemlali' which presented a high palmitic and linoleic content [33, 34].

4 Environmental Conditions of the Olive Specie

The olive tree is a medium-sized evergreen, which grows natively in relatively dry and rustic conditions. The olive tree is cultivated under various climatic and soil conditions and its cultivation is feasible throughout the entire temperate and subtropical zone between 30°–45° [35]. Among the factors affecting plant development, the temperature and the photoperiod exert the strongest affect on reproductive stages. The global climatic changes become a reality, and they will play an important role in plants biological processes in the near future. In fact, plant reproductive phenology is heavily dependent on environmental conditions. Predicting phase development of olive tree is important for different purposes such as assessing the thermal adaptation to new environment and yield models since yield is affected by environmental conditions during flowering. In Horizon 2020, the temperature is expected to increase by + 0.8 to 1.3 °C and the precipitations might decrease by −5 to −8% while in the year 2050, the temperature might increase by + 1.6 to 2.7 °C and the precipitations amounts might decrease by − 10 to − 30%.

5 Temperature

Olive trees develop in area which notes a mean annual temperature varying between 15 and 20 °C with a minimum of 4 °C and a maximum of 40 °C. Temperature determines the course of the various growth and development processes. In arid climate, the olive tree is adapted remarkably well to extreme conditions of the environment, where the heat and summer droughts are almost permanent. The leaf and canopy characteristics presented adapted process to drought. Olive leaf anatomy and surface characteristics are typical of drought resistant sclerophyllous vegetation, including small size, thick cuticule, high stomata density, high pubescence and compact mesophyll cell [36]. The olive tree also has active mechanisms which control the water loss like extended root system and its efficiency to valorize the rare water. High temperatures reduce olive productivity since these destroy the protein structure.

When Temperature reaches 35 °C, photosynthesis is inhibited, and the leaf cuticule is irreversibly damaged. Also, high temperature may cause the fruit drop [37]. So, the pruning type and the architecture tree can modify the temperature of the olive leaf within the canopy, thus affecting water consumption and heat stress [37, 38].

The interest in the effect of temperature on reproductive processes is increasing because the global rise in temperature has affected plant populations. This one induces s a shift in several phenological traits, such as dormancy release and flowering time [39]. Optimal average winter temperature is approximately between 10 and 13 °C [40]. The chilling hours required for flowering is cultivar dependant [35, 41, 42]. Winter chilling is required to release previously initiated flower buds from dormancy and enhance flowering after receiving the required heat requirements. In olive trees, the threshold temperature needed for heat accumulation was equal to 12.5 °C [43]. Moderate temperatures (below 30 °C) during the spring are important for flower development [44].

The olive tree is among the most resistant species to the cold [35, 45]. The olive tree resisted to temperatures of (−12 °C) to (−13 °C) if they occur gradually. The temperatures of (−7 °C) cause significant damage if they occur suddenly [45].

5.1 Rainfall

The olive tree is typically adapted to the Mediterranean climate. In Tunisia, the olive tree is grown in areas with precipitation ranging from 800 mm/year in the north, to 150 mm/year in the southeast. Annual rainfall is irregular and poorly distributed. Olive trees grown under such climatic conditions would adapt to the irregularity of this water regime. In fact; they adjust their water needs by drawing from the soil the little moisture that it can contain due to the root penetration characteristics. Moreover, the exploitation of a large volume of land with the use of low planting density can favorite the tree mechanism adaption [45]. This is the case of the Sfax olive grove where the planting density is 17 trees/ha (24 × 24 m), on a sandy soil where the roots grow up to 6 m deep [45–48]. Being fairly drought resistant, it is traditionally grown in dry conditions. However, its production increases considerably when water supplies complement the rains, especially in areas of low rainfall.

5.2 Light

The most important factor which determines dry matter production in the olive tree is the Photosynthetic active radiation (PAR) intercepted by a crop canopy. Leaves are the active interface of energy, carbon and water exchanges between tree canopies and the atmosphere. The assimilate production depends on leaf area and its light exposure expressed by the canopy volume, the leaf density and the leaf light interception [35, 49]. The leaves photosynthetic response and the distribution of radiation within the canopy, were the results of the the canopy photosynthesis and the biomass production [49–52].

Trees should express along the year high photosynthesis for fruit production by using the synthesized assimilates. All processes along the productive cycle must be optimised and completed without anomalies and disorders which compromise the yield and the life of planting [53]. In an intensive olive orchard trained on vase form, the leaf are index (LAI) varied within the canopy of the olive tree. It was higher on the lower part of the canopy than the upper one for all directions. It was also more important on the the south and east side of the canopy. Although, the incident photosynthetically active radiation (PARI) was quite constant for all directions, the transmitted fraction PAR_T decreased inside the tree canopy. For the vase tree form, The lower part of the canopy was less shaded [35, 49]. It has been demonstrated that fruiting, yield and oil concentration increases linearly with daily PAR up to 40–60% of the incident one [54, 55]. In high-density system (1250 plants/ha), the light interception decreased significantly in the lower canopy (<1 m of the tree height) when compared to central one (1-2 m) and the upper one (>2 m). The authors noted, also, that the largest leaf area was found in the lower canopy of the tree [52].

5.3 Soil

The olive tree is known as a low-quality species in soil quality. It adapts to a wide range of land types on the condition that they are not very compact or poorly drained [56]. The olive trees can grow well even in poor, dry, calcareous and gravelly soils. However, the best soils for annual bearing are the deep, sandy-loam adequately supplied with fertilizers and water. Heavy and low-drainage soils are a limiting factor [56]. The olive tree grows and produces in both low and medium alkaline soils. pH greater than 8.5 reduces growth significantly. In low rainfall areas, olive trees are only effective when planted in deep and sandy soils where the root system can grow vertically and horizontally [46, 47]. The roots of olive trees aged of 80 years occupied a total distance around the tree varying between 17 and 22 m, and their depth reached 3 m [48].

The root system of the olive tree can also adapt to very heavy soil by developing a very superficial and extensive root network. In soils with a non-uniform profile, it has been found that the olive tree develops a radicular system differentiated according to the compatibility and, in particular, the aeration of the soil layers. In irrigated crops, the root system is relatively shallow. Most roots are concentrated to a depth of 70 to 80 cm, and only a few isolated roots can be down to 1.5 m. Most roots were confined to the top soil layers and developed nearby the trunks, developing numerous fine roots, which are very important because they represent the main absorbing surface [57, 58].

6 Shoot Architecture and Olive Tree Biology

Tree architecture describes the plant form which is defined by the spatial organization of the different structural components [59, 60]. The olive tree crown is composed of the trunk which developed the principal branches from which the secondary branches and the tertiary grow. The usual shoot typology is based essentially on the vigor, the nature of the activity (vegetative or reproductive), the position and the age (Fig. 3). Both criteria of the branch length and the presence of certain axillaries productions (serial buds, branches, flowers and fruits are also important for the shoot classification.

The shoots are classified into four categories (Fig. 4):

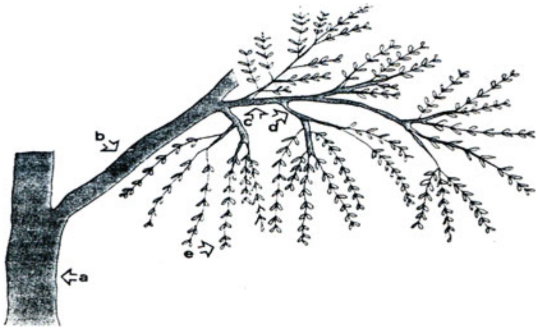

Fig. 3 Various structures of the olive tree crown: (a) trunk or branch order 1, (b) principal or order 2 branch, (c) secondary or order 3 branch, (d) order 4 or fruit branch and (e) shoot branch [61]

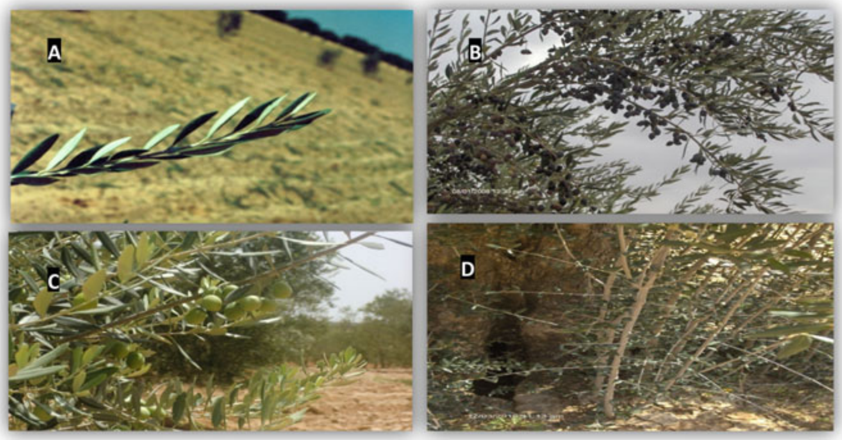

Fig. 4 Shoot types: vegetative shoot (A), fruiting shoots (B), mixed shoots (C), watersprouts (D) [61]

– Vegetative shoots carry only vegetative buds and produce new shoots and leaves. They are located in a vertical position on the canopy periphery and on the upper part. They are more present when the tree is Off-year production, and they can bear little fruit. They show an elongation varying from 20 to 40 cm and long internodes.
– Fruiting shoots produce only flower buds which are more frequent on tree On-year production. They are located on the median or on the periphery of the tree canopy. The fruiting shoot internodes' length is less than 1.8 cm.
– Mixed shoots have vegetative and flowering buds. The flowers and future fruits bear at the shoot base. Mixed shoots remain fully productive for two or four years while the terminal growth remains.
– Watersprouts located on the trunk and branches which are very vigorous. They can grow vertically up to 2–3 m, and they have longer internodes than vegetative shoots.

The reproductive behavior is characterized by an alternate bearing, in which high yield during one year is following by low yield in the following year. The productivity depends both on alternate-bearing-habit and fruit abscission before ripening. Alternate bearing is affected by various factors as water stress, warm soil, climatic conditions, and cultivar. The overlap in the timing of vegetative and reproductive growth produces competition for resources between the two activities. This one generates a pattern of alternate bearing year resources designated mainly to flowering and fruiting at the expense of vegetative growth [62–64]. The bearing status exerts a strong influence on shoot growth as well as on flowering of the following year. A heavy crop load reduces vegetative growth and return-bloom. During the fruiting year (On-year), vegetative growth of new shoots is reduced due to the competition for assimilates between the growing fruits and the new shoots [60]. Tree water status influences the flowers density, the inflorescence architecture, the flower position within the inflorescence and its gender and finally the final fruit set [65–67].

After setting, the fruits become the primary center of attraction sink for metabolites. There are two sources of sugar assimilation processes for fruit growth and lipid biosynthesis. The first source is provided by sugars translocated in the phloem from mature leaves to sites of storage. Mannitol is one of the primary photosynthetic products The second source is the sugar which is developed during the fruit maturity [68]. In the fruit pulp, the abundant sugar is glucose, followed by mannitol, fructose and galactose [70–73]. The relative amount of mannitol in fruit is often used as an indicator of the cultivar potential of oil biosynthesis. The higher amount of mannitol present in the fruit, the more glucose is available to be metabolized [70].

7 Training System for Sustainable Olive Orchard

The olive orchard can be found in very different rainfall conditions, from arid climate to humid one. About 90% of olive orchard area is cultivated under rain-fed conditions and receive annually no more than 350 mm of rainfall. This cultivation system is characterized by the absence of water, the low plantation density and the use of vigorous local varieties well adapted to orchard management. In the last years, the olive oil sector has increasing worldwide importance. So, more olive orchards are planted in the north where the climatic and soil conditions were better. Nowadays, modern orchards are developed in intensified conditions (intensive and super intensive conditions). Thus, the orchards can be classified in three categories (Fig. 5).

The first is the traditional orchards in rain-fed conditions with a density of 14–100 trees/ha and low productivity (650 to 950 kg/ha). The second is the intensive plantations in irrigated conditions with a density of 200–300 trees/ha, trained mainly on an open vase or sometimes on central leader form, and high productivity (2000 to 3000 kg/ha). The third is the super intensive olive orchards which cover around 1500 ha and planted with a density of 1250–1666 trees/ha. This orchards category was introduced in Tunisia since the year 2000 [9]. Moreover, varieties employed in these orchards are foreign varieties like 'Koroneiki', 'Arbosana' and 'Arbequina'. The main factors to be taken into establishing an orchard in rain-fed conditions is the site selection, the environmental conditions (soil, climate), the cultivar, the planting system (density, training tree form) and finally the technical package used. In Tunisia, the orchard density is closely dependant on the average of rainfall: 100–200 trees/ha

Fig. 5 Different growing systems observed in Tunisia: (A) Marginal area in the south of Tunisia, (B) Dry farming system noted in the region of Sfax, (C) Ancient olive tree observed in the region of the Sahel in, and (D) Intensive olive orchard (Personal photos)

where the precipitations varied from 400 to 800 mm/year, 50–70 trees/ha where the rainfall averages were about 250 and 400 mm/year and finally between 17–50 trees/ha where the rainfall was below to 250 mm [9, 64, 74].

The variety is a key factor regarding the adaptability to the different training system. The varieties diffused in the most important olive areas showed some positive attributes appreciated by growers. These characteristics are high oil quality and quantity, soil and climate adaptability and low requirement on specific cultivation techniques. To obtain the best conditions to express good production, trees were planted at right density, pruned in adequate form and trained under standard norms of irrigation, fertilization and soil management. Two main oil varieties are present in Tunisian olive plantations: 'Chemlali' in the south and in the center of the country (56%) and 'Chétoui' in the northern area (12%).

However, the adoption of a technological package appropriate for each planting system (choice of variety, pruning, irrigation, fertilization) is necessary. The type of pruning and the training system are two of the major factors in successful tree performance and therefore orchard productivity. The best training system is the one that allows high yield of excellent quality and can be obtained at minimum cost without negative side effects on plant performance and orchard management [52, 72, 73]. It would be important that olive trees can express along the year, high photosynthesis and high use of assimilates for fruit production. All the processes must be optimized toward the productive cycle which would be completed without anomalies and disorders and disturbing of the yield and the planting life [60, 62, 74]. The most frequent training systems in olive growing are the vase form, the free form and the central leader form all compatible with minimum pruning strategies (Fig. 6).

The vase and the central leader form are suitable for manual and mechanical harvesting. The central leader form-Trees was a tree which trained to a single trunk with primary branches arranged in a helicoidal fashion along the central axis for a maximum occupation of space and minimum overlapping. The primary branch showed decreasing length from the base to the top of the tree which assumes a conical shape. The open vase form is the most ancient and common form in the traditional olive orchards. It is formed of a single trunk that its height was equal to

Fig. 6 Training systems in Tunisian olive growing: (a) central leader form, (b) vase form and (c) free form [38]

0.7 m and 3 to 5 branches are oriented in different directions. Most of the fruiting shoots are born on secondary and tertiary branches. The free form is a free-canopy shape which is obtained with minimum pruning. Primary branches in free form are originating directly from the trunk of the tree or inserted directly from the base of the tree. The canopy is allowed to grow freely [16, 37, 38, 75, 77].

These three tree forms were developed and kept through a study set up in 2002 on different olive varieties planted in central Tunisia [38]. The experimental set-up was based on eight varieties: 'Chemlali', 'Chetoui', 'Koroneiki', 'Coratina' (olive oil cultivar), 'Manzanilla', 'Meski', 'Ascolana' (table olive cultivar) and 'Picholine' (a double aptitude cultivar). 'Chemlali', 'Chetoui' and 'Meski' cvs., are the most important Tunisian olive varieties. Plant growth parameters and yield components were monitored yearly for the eight years of experiment, from 2005 (entry into production) to 2012 (last harvest). The free form trees have an important increase of their canopy volume comparing to the two others form. It varied from 6296 m^3 ha^{-1} for 'Meski' to 12,073 m^3 ha^{-1} for 'Koroneiki'. On the two other forms (central leader form and open vase form), trees showed an important reduction of their canopy, ranging between a minimum of 3001 m^3 ha^{-1} and a maximum of 9201 m^3 ha^{-1}. The total volume reached 12,000 m^3 $ha^{-1.}$ in the intensive conditions of our experiment. This result corroborates previous works indicating that the total volume of trees in the region of Andalucia, in non-irrigated land reached 8000 to 10,000 m^3 ha^{-1}. In irrigated land, it ranged between 12,000 to 15,000 m^3 ha^{-1} [76].

The cumulative yield, during the eight production years (2005–2012), was the highest on the free form. For this form, 'Koroneiki' noted the highest yield equal to 42,177 kg ha^{-1}. Furthermore, important cumulative yield was noted for 'Koroneiki' trained on the open vase form (22,213 kg ha^{-1}) and for 'Chemlali' trained on central leader axis (16,131 kg ha^{-1}). Thus, the open vase form and the free form systems are highly productive, easy to develop (received little pruning and no pruning at all, respectively). However, 'Koroneiki', 'Chemlali', 'Coratina' (oil varieties), and 'Picholine', 'Meski', 'Manzanilla' and 'Ascolana' (olive table varieties), showed good suitability mainly due to their growth habit, high yield, and less alternate bearing. Moreover, 'Chétoui' seems to be not adapted to the southern Tunisian region, even under intensive conditions [38, 74].

8 Orchard Management for Sustainable Olive Cultivation

8.1 Soil Management

In arid environment, the soil is the basic element in plant life. Indeed, it acts as a source of water and nutrients for plants. The rains maintain the water reserves of the soil, which will be returned to the plant during the different active phases of development. In rain-fed cultivation, under arid conditions, this role of sink becomes very important since the olive tree is below its needs in water which are estimated at

450 mm of rain per year. The olive tree adapts to a varied soil type due to its rusticity properties. It grows in the relatively humid northern areas of Tunisia on soils that contain on average more than 1.5% of organic matter. In the arid southern areas of Tunisia, it is most often found on very poor skeletal soils that contain on average 0.1 to 0.5% of organic matter [48, 75, 76].

The soil management is oriented to insure productivity and survival of the plantation, under limited conditions and highly variable rainfall, using a combination of low density of trees and elimination of adventitious vegetation to limit competition for soil water. In the center and in the south of Tunisia, the dry farming was frequently used. It consisted of soil tillage 3 to 6 times per year. It 's deeply in the humid and cold season to eliminate weeds and facilitate water infiltration in the soil, and it is superficial in summer to limit water evaporation [9, 75]. The tillage increases the permeability of the tilled layer temporally, but in the long run, it may lead to the formation of a plough pan and the deterioration of surface soil structure, thus adversely affecting soil and water conservation. Besides affecting the performance of olive trees, there are consequences at the watershed level, linked to surface water management [81]. Also, continuous tillage at a soil depth of 15–20 cm damage the fine roots, which is the most efficient in water and nutrient uptake, causing deficiencies in olive trees.

However, the mean value of soil loss by erosion varies from 26 to 51 t ha^{-1} $year^{-1}$. Most of the soil erosion in olive groves in Mediterranean environments occurs in a few major events in late summer-early autumn, due to the erosive precipitation events in that season and to the lack of vegetation at that time linked to tillage operations. In winter, the risk of erosion is often lower due to the presence of plant cover [81]. Moreover, erosion rates become higher and unsustainable when olive cultivation was pursued systematically on slopping areas and in a homogeneous olive covered landscape. During these decades, the major effort regarding erosion control in olive orchards has been the development and expansion of the use of ground cover in the orchard lanes to prevent erosion and improve soil properties [16, 81]. Some solutions like recovering the soil with a mixture of cereals and leguminous and using pruning residues by mulching and compost of olive oil residues can conserve water resources, improve nutrient recycling and humidification process efficiency and therefore increase productivity [82]. The use of tree pruning residues as mulching improved soil physic-chemical properties and increased soil microbial and faunal activities. In fact, pruning residues decompose slowly due to their high content of cellulose and lignin, which makes it possible to ensure long-lasting soil protection and organic carbon accumulation. Some studies have reported that soil Carbon (C), Nitrogen (N) and Phosphorus (P) status was improved after the amendment of pruning remains. Pruning residues provide about 1000–2500 kg C ha^{-1} $year^{-1}$. Thus, it's an important source of carbon preferably used after a cycle of stabilization composting [83].

The leguminous cover crops presented considerable microbial diversity and enzymatic activities, which may contribute to promote and conserve soil quality, improve the profitability and the sustainability of rain-fed olive orchards [77]. However, it is important to mention that obtaining an effective ground cover remains a challenge due to the severity of soil degradation combined with the intensive traffic in the olive orchard. It also remains relatively a large uncertainty regarding the impact of the competition of the cover crop in years of limited rainfall under the changing climate scenarios with higher temperatures and scarcer precipitations [82, 84, 85].

A significant amount of wastewater is produced by the olive industry, from both olive mills and factories processing olives for table consumption. The Olive Mill Wastewater (OMW) is rich in organic matter and an important source of nutrients for plants [86, 87]. The olive mill wastewater (OMW) contains 83–94% of water, 4–16% of organic matter and 0.4–2.5% of minerals salts [88]. The OMW is known to increase soil organic matter and the concentration of essential inorganic elements for plant growth [86]. An application of OMW induced a temporary decrease in soil pH, an increase in salinity and elevation in phenol concentrations) [89, 90]. Negative effects of OMW on soil properties have also been recorded, including the immobilization of available Nitrogen [91]. Addition of fresh OMW to soil increases the number of soil microorganisms (bacteria, yeasts, and fungi), and induces a change in the microbial community [92]. Following experiments done in rain-fed conditions of Tunisia, an application of 50–100 m^3 ha^{-1} of the olive mill waste water (OMW) induced an increase of the soil fertility and the yield, but no effect was observed on the oil accumulation [70, 79, 93].

8.2 Water Use

Water scarcity in Mediterranean countries will be progressively aggravated by climate change, population increase, and finally urban, tourism and industrial activities. These countries are characterized by hot dry summers, mostly rainy winters and partially wet spring and autumn. Rainfall is traditionally the main water supply. Indeed, water scarcity in Mediterranean countries is destined to gradually become worse as regards the more frequent and severe droughts events caused by climate change. To ensure regular crop yields and to reduce inter-annual yield variability, the scarce rainfall has to be supplemented by irrigation to avoid plant water deficits [58, 69, 77, 94–101].

Importance of Water on Physiological Needs of the Olive Tree

Most of the biological processes for growth and production occur during the dry season. When water stress is present, shoot growth is reduced, and flowering and fruiting are affected. Floral quality and effective pollination have a significant influence on the fruit set, on the fruit number and finally, on the final crop of the olive orchard. They are strongly influenced by environmental conditions and by a varietal factor [65, 74, 91, 92, 98, 99] Indeed, it was shown that water stress felt at early stages of fruit development reduces consistently yield and fruit size due to negative effects on fruit set [100]. Olive trees are more tolerant to water deficit during the second phase of fruit development, *i.e.* when pit hardening occurs (Table 2).

Table 2 Critical period of water stress for olives and their effects [37, 105]

Growth stage	Effects of water stress
Shoot growth	Reduced shoot growth
Flower bud development	Reduced flower bud formation
Flowering	Aborted pistil
Fruit set	Reduced fruit set, Alternate bearing
Fruit growth	Decreased cell divisions (1^{st} stage) Reduced fruit size due to the decreased cell expansion(3^{rd} stage) Small fruit and shrivel fruit Reduced oil content

Water Requirements

In areas with precipitation of 450–650 mm/year, the water needs of olive trees are completely fulfilled. In some regions of Tunisia, the olive plant can survive even in areas with only 200 mm of rainfall but needs at least 400 mm to be productive. An estimated 312 g of water must be transpired to produce 1 g of dry matter in olive, whereas 400 and 555 g are needed in *Citrus* and *Prunus* species, respectively. Water consumption by olive is about 30 and 40% of that of *Citrus* and *Prunus* species, respectively [35]. The high water use efficiency of olive is considered to be a result of adaptation to drought conditions. The adaptation mechanisms were conferred regarding the root system (its distribution, its hydraulic characteristics, and anatomy), to the leaf characteristics (presence of stomata and peltate trichomes, small leaves) and finally the tree size and canopy architecture [38, 58, 105].

Several methods, approaches, and concepts were developed during the last decade to determine more precisely the amount of water requested by trees for their growth and production [107–109]. The most common and widely used approach is that of the FAO, which was adopted in 1998 as the standardized method [108, 110]. Irrigation amounts (IA) are determined through an estimation of the crop evapotranspiration (ET_c) for the non-limited soil water status conditions, which depends on multitude factors [69]. This is calculated from the potential evapotranspiration (ET_0) for non limited available water, a coefficient (K_c) called the crop coefficient and a coefficient (K_r) related to the percentage of ground cover. Water requirements (ET_c, mm) were monthly determined following the FAO method [110], as $ET_c = ET_o \times K_c \times K_r$.

The meteorological-based irrigation scheduling approach of the FAO is being adopted by the Tunisian farmers to irrigate [74]. The maximum olive tree water requirements taking into account tree age and soil coverage. For Tunisian climatic conditions, Average ET_0 varied between 1200–1400 mm year^{-1}, maximum potential ETc could be varied from 5000–7000 m^3.ha^{-1} year^{-1}. The irrigation amount is equal to the difference between ET_C and the effective rain which is equal to 70% of the rain quantity.

Irrigation Methods

The olive tree's outstanding adaptation enables it to grow and to produce commercial yields under rain-fed conditions in areas where the average rainfall varied from 100–500 mm in areas where planted olive trees mm and where the dry season can last for 5 to 6 months like noted in Tunisia. The old practice of applying just one or very few irrigation events on the dry season has been called supplementary or complementary irrigation [108]. The olive tree has a marked respond to the addition of any quantity of water, even if only small doses of water are applied during the critical period. Farmers usually tend to apply less water quantity than what olive tree needed for full production and to distribute it to the maximum surface. They try, also, to avoid water stress when the crop is in sensitive development phase (fruit set and fruit growth). This strategy is called Deficit Irrigation (DI) which improves water productivity based on scientific principles, attempting to produce near-maximum yields even if crops are provided with less water than they would otherwise use. Strategies of DI were proposed to control the vegetative development of trees through a rigorous application of water without major effects on yield [97, 111, 112]. It is a useful practice. It aims to apply a fraction of crop evapotranspiration (ET_c) throughout the irrigation season called sustainable deficit irrigation SDI [93, 109, 110]. Alternatively, during specific developmental stages according to the physiological aspects of plants called regulated deficit irrigation RDI [93, 104], but in a rational way to keep the crop performance as close as possible to its maximum potential [97, 108, 113–115]. When a RDI strategy is applied, full irrigation is supplied during the drought-sensitive phonological stage (critical periods) of fruit trees, and irrigation is limited or even unnecessary if rainfall provides a minimum supply of water during the drought-tolerant phonological stages [97, 100, 104]. Another used strategy has been called partial root-zone (PRD) based on irrigating only one part of the root zone, leaving another part to dry to a certain soil water content before rewetting by shifting irrigation to the dry side [97, 104, 114, 115].

Under the semi arid climate conditions of central Tunisia, an experiment was conducted to study the effect of sustainable deficit irrigation on the behavior of local and foreigner varieties [65, 74, 94]. In this experiment, three irrigation treatments were applied on five varieties with different water amounts of 20% ET_c, 50% ET_c and 100% ET_c, where ET_c is the crop evapotranspiration. Maximum biannual productions were given by 'Picholine' (23.0 kg tree^{-1}) and 'Coratina' (18.0 kg tree^{-1}) irrigated at 100% ET_c, by 'Manzanille' (33.3 kg tree^{-1}) supplied with 20% ET_c, by 'Chétoui' (27.1 kg tree^{-1}) cultivated at 20% ET_c and by 'Chemlali' (26.4 kg tree^{-1}) receiving a water amount of 50% ET_c. Maximum daily records of stomatal resistance (R_s) were observed at midday, showing significant differences between treatments for the cultivars 'Chétoui', 'Coratina' and 'Chemlali'. Highest variations were provided by 'Chemlali', which seemed to be the most able to regulate stomata aperture. Irrigation amounts varying between 20% $ET_{c,}$ and 50% ET_c can present the effective water needs of the studied olive varieties adequately when they are cultivated under the conditions of Southern Tunisia. According to the expected fruit crop load, the irrigation volume is adjusted. In the particular case, the smallest irrigation dose (80 mm) can be recommended for low fruit loads years [74].

Water Quality

The limited water availability in arid and semi-arid regions and the increased need for good water quality for urban use, restrict the use of fresh water for agriculture. Nowadays, the controlled use of marginal water (saline water and treated waste water) to improve the qualitative characteristics of horticultural products is becoming more and more important, particularly under actual conditions of limited water resources and rainfall scarcity [116, 118].

The use of saline water in irrigation is not necessarily detrimental to the environment, but the soil evolution must be closely monitored for sustainability. In very arid environments, rainfall could be insufficient to remove salts through the natural soil flushing at the rate they are added by irrigation water. Furthermore, the quality of surface water is sometimes compromised by its mixing with poor-quality drainage [37, 58]. Salinity effects on yield depend on its concentration but even though cultivar-tolerance. In fact, most of the cultivars trained under semiarid conditions may develop well with no significant reduction yield with an electrical conductivity (EC) ranging between 3 and 6 d Sm^{-1}. The limit of salt content threshold has been established at 8 gL^{-1} of solid residue [118]. The use of saline water for irrigation should not be applied without taking account into consideration of different surroundings conditions where it is used, particularly the water salinity level, the soil type, the irrigation system adopted, the degree id the crop salt, the plant growth and the climatic conditions [118].

The use of recycled wastewater for irrigating olive trees is an interest option. Many studies [116, 119] showed that the application of treated waste water (TWW) at a reasonable rate improved growth and productivity of some species. However, the main problem that can arise from the excessive and continuous application of TWW is phytotoxicity due to the high salt content and heavy metals, which may induce risk for human health [37, 116, 122].

8.3 Fertilization Strategy

Fertilization tends to satisfy the nutritional needs of orchards, to obtain a high-quality crop and must avoid excessive and systematic application of fertilizers [16, 120, 121, 123, 124].Thirteen nutrient elements, which are mineral elements, constitute the object of fertilization. All together, they represent only about 5% of the dry weight of the olive tree. These nutrient elements are divided into two categories: macronutrients (N, P, K, Ca, Mg and S) and micronutrients (Fe, Mn, Zn, Cu, Mo, B and Cl). The leaf-nutrient analysis indicates the tree nutritional status and represents an important tool for determining fertilization requirements.

Nitrogen exerts a significant effect on plant growth and increases the percentage of perfect flowers to avoid biennial bearing [37, 102, 125]. Lack of nitrogen leads to decreased growth, shorter shoots, reduced flowering and decreased yield. The time of N fertilization in rain-fed conditions of Tunisia is recommended during autumn (vegetative growth) and spring (budburst). The quantity of N applied (33%) varied between 3 kg per tree in the North to 5 kg per tree in the centre and the south. It will be important to mention that N must be applied only when the previous season's leaf analysis indicates that nitrogen concentration is below the standard deficiency [71, 73, 128, 129]. A significant and progressive decrease in olive yield when nitrogen was eliminated from the fertilization plan for four years, in comparison with treatments where nitrogen was applied annually [130]. Nitrogen concentrations in the leaf under 1% lead to the formation of imperfect flowers [102, 131].

Phosphorus is a component of high-energy substances such as ATP, ADP, and AMP it is important for nucleic acids and phospholipids. It affects root growth and maturation of plant tissues and participates in the metabolism of carbohydrates, lipids, and proteins. Due to its extensive root system, the olive tree absorbs adequate quantities of phosphorus [37, 130]. Phosphate fertilization could be tried under the following situation: in the shallow poor soil, in orchard fertilized a long time with nitrogen fertilizers, in high soil $CaCo_3$ and finally in the soil of low pH. The optimal ratio of phosphorus: nitrogen is 1:3. The applied quantity does not exceed 1.2 kg of Phosphorus applied (Super phosphate 45%) in rain-fed conditions of Tunisia (IO 2017)[133]. It is very rare to reach phosphorous deficiencies since it is easily reused by the trees and phosphorous removal is low. Taking into account that the reserves of phosphate rock are definite, more responsible use of (P) fertilizers is required to minimize the overdose [123].

Potassium is a key element in the fertilization of olive orchards, its concentration in the fruit is highly correlated with the improvement of fruit quality and oil accumulation. Potassium is important for its involvement in the following processes: carbohydrate metabolism, metabolism of (N) and protein synthesis, enzyme activity, regulation of the opening and closing stomata and alteration of photosynthesis and respiration [132]. Potassium is an important element in the olive culture because it plays an important role in growing and water-use efficiency [133] and olive fruits have high potassium requirements [134]. Around the Mediterranean Basin, olive trees have been traditionally grown on calcareous soils under rain-fed conditions where potassium deficiency has been described as one of the most important nutritional problems even in trees cultivated on soils with adequate potassium content [137].

For the rest of the elements, it seems that boron (B) has effect on blooming rate and yield [137, 138]. Adequate boron nutrition is critical not only for high yields but also for the high quality of crops. It is well known that boron plays an important role in pollen germination and pollen tube growth [140]. Other studies demonstrated the importance of boron nutrition in flower quality and fruit set [135] or the existence of a close relationship between the boron nutritional status of trees and olive yield [142]. Another important element is iron (Fe), especially in calcareous soil. Olive trees fertilized with $FeCO_3$ showed greater leaf chlorophyll concentration, as well as greater yields.

Foliar fertilization is a widely used practice to satisfy plant requirements and correct nutritional deficiencies in plants. Foliar spraying of nutrients is in general helpful to satisfy plant requirements and has high efficiency, especially in nutrient-fixing soils or in arid zones where a lack of water, under low-rainfall conditions in summer, drastically depresses the absorption of soil nutrients. Foliar fertilization has the advantage of low application rates, uniform distribution and quick plant responses to applied nutrients [70, 123, 137]. In Tunisia, some experiments on nutrients fertilizers were applied by the foliar application in irrigated condition on olive table variety 'Picholine' [69] and in rain-fed condition on oil variety [42, 73, 127, 142]. Treatments rich with nitrogen and boron caused a significant decrease of total phenols and tocopherols contents and induced qualitative changes in the profiles of minerals, phenols, tocopherols, and carbohydrates in fruits issued of 'Picholine' conducted under irrigated conditions [72]. The two compounds for foliar fertilization (Nitrogen and boron) used in simple or in combined form improved the mineral status of the 'Chemlali' variety under rain-fed conditions, enhanced flowering and pollination process [43].

8.4 Pest Control

The olive tree is attacked by various insects, fungi, bacteria, and viruses. The most serious insects' attacks include those by bratrocera oleae (*Diptera: Tephritidae*), the prays olea (*Lepidoptera: Yponomeutidae*), the black scale Saissetia oleae (*Homoptera: Coccidae*), the Eupyllura olivina (*Homoptera: Psyllaae*) and some secondary scolytids like *Hylesinus oleiperda* and *Phloetribus scarabaeoides* (*Coleoptera: Scolytidae*). Various methods of controls have been used like chemical treatments, intergraded pest management using proper cultural practices that maximize biological prevention (soil management, pruning, irrigation..) and the use of sterilizing male or female, pheromones and biological methods [16, 37, 144, 146].

The principal pathogens which caused damaged are the *Cycloconium oleaginum* known as bird's eyes on the upper part of leaves, the *Armillaria mellea* a new disease which attacked new orchards on trunk and roots and finally *Verticullium dahlia* which fungus enters and groves into the vessels resulting in wilt and death of plants. All these pathogens are treated with biochemical products (copper products), elimination of infected parts, solarisation. An important bacterial agent (*Pseudomones phytophtora pv savastanoi*) created rough galls or swelling on twigs, branches, and trunk. The occurrence of infection requires openings provided by leaf scars and pruning wounds. So, it's necessary to make preventive fungicide sprays to reduce bacterial entry through the scars [37].

Increasing public sensitivity towards environmental pollution and the release of treatments on human health and the foods, a new strategy Integrated Pest Management (IPM) has been developed. The IPM is an efficient approach to pest managemnt respecting the environment and combines common-sense practices. IPM programs are based on the study of the life cycles of pests and their interaction with the environment. This study gives informations which is used in combination with available pest control methods, to manage pest damage. This management is set up with the most economical means and with reducing possible hazards to people, property, and the environment [145]. lIn contrast, organic food production applies many of the same concepts as IPM but limits the use of pesticides to those that are produced from natural sources, as opposed to synthetic chemicals [146]. In Tunisia, efforts have been done to develop biological methods in IPM regarding the Prays Olea by using Trichogramma [144, 147].

9 Conclusions

Olive cultivation is widespread throughout the Mediterranean region and also is now grown in countries not traditionally associated with its cultivation. The olive tree is not only a significant food source but also contributes to human health. Olive products represent an important component of the Mediterranean diet, widely associated with improved health, as well as protection against cardiovascular and colon diseases, breast and skin cancers. Although, the olive tree is characterized by mechanisms of adaptation to main environmental stresses; therefore it can grow in different conditions varying from arid zones where natural's resources are very limited to humid one with better conditions. In some areas, the olive tree seems the only livelihood. So, the "Farmer's opinion" is becoming more and more aware for the effect of climatic changes. For an economic and sustainable system of agriculture, a relatively new concept of olive growing production should be adopted by farmers as an integral part of agricultural development plans. So, this review detailed some techniques used for a productive and sustainable olive cultivation in different conditions. Appropriate cultural practices are based on a good understanding of the natural environment and all its soil, climatic, agronomic, biological and social component parts and their possible interactions.

10 Recommendations

For the improvement of the olive sector sustainability, general guidelines must be respected throughout the valorization process of our olive products (oil and olive) regarding the different stakeholders the olive grower – the oil mill manager- the conditioner and finally the exporter. So, it will be necessary to:

-Improve the olive productivity through the good use of adapted technical package to different conditions

-Enhance the quality of our oil by adoption g good harvesting conditions, efficient processing methods, adequate packaging, development of products with the protected designation origin (PDO) and Protected geographical indication (PGI)

-Valorize by-products olive tree by using the pruning residues, the mill waste water …

-Move to organic olive cultivation with greater value especially for orchards which are cultivated under rain-fed conditions with low or no inputs

-Promote export policy, search new markets and innovate marketing pathways

-Encourage the development of cooperative structures to increase productivity and adding together the strengths of the various stakeholders in the sector.

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Tunisian Date Cultivars: Economical Aspect, Physicochemical Properties, Sensory Characterization and Potential Valorization

H. Ben Ismail and D. Ben Hassine

Abstract The date palm (*Phoenix dactylifera L.*) is one of the oldest cultivated species in the Middle East and North Africa region particularly Tunisia, known by the most commercialized cultivars *Deglet Nour, Allig, Khouat Allig* and *Kenta.* It is now also cultivated in many arid and semi-arid regions around the world. The date palm is also one of the crop species generating the most important income and represents a major source of export earnings and livelihoods for millions of rural smallholders. It ensures food and nutritional security for millions of users. Thus, the economic activities generated by dates production can positively contribute to the achievement of certain goals of sustainable development. This chapter book aims to promote dates as special fruits for economic, environmental and social development; with regard to nutritional value and bioactive properties, since the fruit is recognized for its high content of carbohydrates, dietary fiber, and ash. This fruit is also a rich source of high value antioxidant compounds as polyphenols. The history and symbolic meaning, the importance of dates and their traditional use were investigated. For example, in Tunisia, seeds palms are used not only as byproduct for food industries but in cosmetic to prepare eye Pencil "KOHL", and to create "Koffa" which is a hand bag. The sensory characterization of Tunisian dates is an essential step in chemical analysis for defining the characteristics and value of food products. Mainly, Degletnour cultivar was the most appreciated for its organoleptic properties. Several potential valorization of date palm fruit and its coproducts were highlighted in this chapter book to give a lecturer a large overview. As example, *valorization in food industries, animal feed, artisanal products, Energy production, etc*

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Keywords Tunisian date · Biochemical composition · Sensorial characterization · Typicity · Valorization

1 Introduction

There are more than 600 date cultivars in the world that differ in form, nutritional and organoleptic characteristics [1]. The Tunisian date palm is represented by more than 250 cultivars [2], which are unfortunately threatened by the expansion of *Deglet Nour* [3]. This fruit is a model of plant bio resource rich in nutritional and therapeutic qualities. Indeed, dates are known for a high content of carbohydrates (77–84%), a source of dietary fiber (6.26–8.44%) and ash (1.49–1.79%), but low in protein (1.47–1.68%), and in fat (0.52–1.41%) [4]. This fruit is also a rich source of high value antioxidant compounds as polyphenols. These nutritional characteristics allow its valuation and potential for use in food industries.

Due to the bioclimatic diversity of Tunisian regions, the production of nearly 250 cultivars of dates over a period stretching from early October to the end of December was noticed. The most commercialized cultivars are: *Deglet Nour, Allig, Khouat Allig* and *Kenta*, however, owing to the overproduction of dates, and the limited processing during storage and harvesting, huge losses are induced especially for low grade fruits [5]. Low grade fruits are generally used to feed animals [6]. In Tunisia, the other kind of waste such as seeds, palms are used not only as byproduct for food industries but in cosmetic, traditional industry to create "koffa" for example which is a bag. This chapter aims to demonstrate the importance of dates, particularly Tunisian ones and their valorization in several sectors. The role of dates processing and its by-products for the Tunisian economy as well as its role in social improvements was also elucidated. The goal is also to summarize the principal studies related to date fruit, their physicochemical and sensory evaluation.

2 History and Symbolic Meaning

There is evidence that the date palm was cultivated as early as 4000 BC, because it was used for the construction of the Moon God Temple in southern Iraq-Mesopotamia [7, 8]. For that reason, date palm is probably considered as the most ancient cultivated tree in the world. It also has a religious significance because it has been mentioned in the Jewish, Christian and Muslim religions [9]. For the Jews, this plant was considered one of the seven sacred fruits namely: wheat, barley, grapes, figs, pomegranates, olives and dates. Islam is the religion that has been most interested in the date palm and its fruits. The Holy Qur'an mentions the date in 17 suras (chapters) and 20 verses of the 114 original suras and 6,263 verses. It is reported that the prophet Mahomed said that the date palm cured many troubles, and he urged Muslims to eat the date and heal the date palm. For Muslims around the world, dates are usually used to break the fast during the holy month of Ramadan [9]. As sugar did not appear until the fifteenth century, sweet foods such as dates and honey were used as sweeteners. Dates were also part of the composition of popular recipes in the middle Ages [4, 10, 11]. In the early years of the Nineteenth century (1912), the date palm was introduced into the western part of North America (Colorado Desert, Atacama Desert and other regions). Now, this tree is widely distributed across the desert regions of North Africa and The Middle East [9].

This fruit has an amazing signification. It was found that this term comes directly from the Greek "*Dactylos*", which means the "finger". It is the elongated shape of the fruit that gave it its name [8]. From Tozeur to Nefta, the oases of southern Tunisia look like mirages. This is where Deglet Nour, the most prestigious type of dates, is grown. It is also the most exported Tunisian variety. Its name means "fingers of light" because it is almost translucent, revealing its core [8].

3 Importance of Dates

Symbol of fertility and prosperity of the Saharan and Pre-Saharan areas, the date palm extended from the Middle East, in India, in China, across Africa and to the distant Pacific islands. This tree, cultivated by humans for millennia, is found in the oases of southern Tunisia which offer a healthy ecological system where the tree produces a delicious and valuable fruit [12].

The Tunisian date sector represents 6% of Tunisia's overall agricultural production, 19% of total agricultural exports and it is a very important source of employability since it implies more than 50,000 families. They are implanted mainly in the South of Tunisia where they are considered as life sources for many families. The date chain is one of the most dynamic of Tunisian agriculture. Date oases cover a total area of 41 thousand hectares including 8363 ha (74 oasis) in the delegation of Tozeur [13]. Tunisian palm groves cover 1.9% of total tree areas. They are also important for the ecology of the country, since the date palm adapts perfectly to various environmental stresses [14]. According to their geographical and bioclimatic situation, three types of oases are distinguished: the continental oases of Djerid (Tozeur and Nefta) and Nefzaoua (Kebili and Douz), the coastal oases of Gabes and the oases of altitude of Gafsa [12]. This bioclimatic diversity allows the production of more than 200 cultivars of dates over a period stretching from early October to the end of December.

The most commercialized cultivars are: *Deglet Nour, Allig, Khouat Allig* and *Kenta*. The excellent conservation capacity of the *Deglet Nour* variety in a cold room allows it to be marketed all year long. It's important to notice that 90% of the national production of dates comes from *Deglet Nour*, 30% of the production from Djerid and 55% from Nefzaoua [13].

The total production of dates has reached 305 thousand tons in 2016/2017 against 241 tons 2015/2016 which represents 26.3% rate of increase. As cited by [15], Tunisian date palm fruit is also a popular product on the world market since 60% are intended for export.

The export season of 2017/2018 was closed with a growth rate of 18% in terms of quantity and 35% in terms of value compared to the season 2016/2017. So, the number of exported dates, by the end of September 2018, has reached a high record with 130 thousand tons worth 770 million dinars compared to 110 thousand tons worth 570 million dinars during the season 2016/2017. This season was exceptional because the export of biological dates registered a growth rate of 31% and increased from 8 thousand tons to 10.5 thousand tons, which corresponds to an increase in terms of value of 54% (from 52 million dinars to 80 million dinars). According to [16], the total date production in Tunisia was, in 2018, around 288.000 tons with 129.346 tons exported, while the total date production was amounted 340.000 tons with 113.553 tons exported, in 2019. Recently, the Economist Maghrebin web Journal [17] reported that during the first eight months of the current year 2020, Tunisia has exported 74.1 thousand tons of dates for a value of 496.3 million dinars, against 77.9 thousand tons exported during the same period of 2019. It is also important to know that in Tunisia, the 2020/2021 season promises to be delicate for the date sector on the export side. In fact, this sector will be impacted by the economic slowdown linked to the second wave of the COVID-19 pandemic. According to Tunis Afrique Presse (TAP) [18], exporters are still reluctant to start purchasing dates from producers because of their financial fragility. This situation could in particular have repercussions on other players in the supply chain such as storage centers, processing and packaging units or even producer prices.

In addition to the high quantities exported in the season of exporting dates, we find a great diversity of markets, where the Tunisian dates were exported to 85 countries spread across five continents. This increase is due to the development of export patterns such as Morocco (42%), United States of America (80%), Canada (76%) and Malaysia (55%) [19].

4 Traditional Use of Dates

Date consumption is a tradition and even a habit mainly for Muslims. In fact, date palm fruit was very appreciated by Prophet Mohammad. This fruit has long been a staple food in the Middle East. This is not only very beneficial for our body, but it is also a staple of the prophetic tradition. It was used to feed Miriam, mother of Moses, who was about to give birth, weakened and alone. In surah Miriam verses 23–26: "*And the pains of childbirth drove her to the trunk of a palm tree (23), but he called her from below her, do not grieve; your Lord has provided beneath you a stream (24), and shake toward you the trunk of the palm tree; it will drop upon you ripe, fresh dates (25), so eat and drink and be contented and if you see from among humanity anyone, say, 'Indeed, I have vowed to the Most Merciful abstention, so I will not speak today to any man' (26).* And of course, the main consumption habit remains to break the fast in the month of Ramadan [20].

The natural sweetness and the importance of dates palm fruits make them the perfect ingredient when used in baked goods, dairy products, cereals and confectionery. Below we mention some traditional Tunisian dishes prepared with dates. The main uses of dates in Tunisia mentioned below were compiled on the basis of our investigation (not yet published) which was conducted on housewives in different regions of Tunisia. First, we quote *Maajoun* which is a kind of paste made with pitted date fruits and olive oil, then modeled in the form of a ball. Then the example of *Abboud* which is a date paste cooked and seasoned with coriander, mugwort, anise seeds, rosemary, juniper, fenugreek and green cumin. This mixture is dried in the shade. *Robb* dates or date's honey is prepared by cooking dates and water on low heat. The date's cores are then removed, the fruit are pressed, the obtained juice is filtered and then cooked over low heat until obtaining a blackish syrup. In other regions, local populations consume *R'fiss* which is a date paste kneaded with hot grilled semolina (wheat or barley) and butter or olive oil, then shaped into regular pieces. For others, the date paste is heated with butter, traditional bread (*Rgag*) and olive oil. And when dates are macerated in warm water which will be used after filtering to soften the couscous the preparation is called *Mressa*. In Degueche, this filtrate, subjected to fermentation, is used for the conservation of olives and peppers. In Temerza the typical recipe is the *Melbouza*, a date paste kneaded with olive oil, salted butter, grilled semolina and some desert herbs. The *Dhouaba*, is the typical recipe from Hazoua (Tozeur), obtained by cooking the date paste, semolina and the butter together. *Sfah* is a couscous with added pitted dates, almonds and oil or milk. And finally, *Makroudh* is also a typical recipe made with date paste, semoulina, salt, butter, sugar, fried then introduced in honey.

5 Identification of Common and Non-common Cultivars

Commercially, the name "common dates" is used to differentiate *Deglet Nour* from the rest of the cultivars. It is only applied to dates from Tunisia and Algeria. Originally, these cultivars constituted the majority of oasis plantations in North African countries, and are the result of natural selection with active human intervention. In the past, two important factors were involved in spreading and consolidating the strategic importance of these palms: their adaptation to the natural environment and their ability to feed the Saharan population. Common dates are divided into three categories: Early and fresh dates, soft dates and dry dates.

5.1 Early and Fresh Dates

The varietal diversity of the date palm in North Africa makes it possible to have dates on the tree for a long period of the year, up to 5 months between July and December. Early dates are generally very sweet and fragrant dates, but do not conserve well.

The fruit must therefore be consumed in a relatively short period of time. For the inhabitants of the oases, it constituted a significant food resource for a period of two months. Today, early and fresh dates are not very commercialized, but these cultivars continue to be popular in the region where they were cultivated. Fresh dates include cultivars that have the particularity of being consumed at the Bisrmaturity stage (Blah, or Khalal, depending on certain local appellations). At this stage, the fruit is not physiologically mature, but is characterized by a high sugar content and low tannin content.

5.2 Soft Dates

Soft dates are cultivars that have a soft texture, but are well preserved and mature. Before the expansion of *Deglet Nour*, the majority of the plantations in the oases of North Africa consisted of these cultivars. The trees are vigorous, hardy and their production is the basis of the inhabitants' food ration. The dates were kept in sacks or skins in satisfactory conditions until the next harvest season. Typical examples of this category of dates are: *Allig* in Tunisia, and *Ghars* in Algeria. It is unfortunate that these hardy and well-adapted cultivars are not included in the new plantations of Tunisia and Algeria, which consist exclusively of *Deglet Nour* [21].

5.3 Dry Dates

In this category we find common dates with dry texture, thick pulp and light color. They are very sweet (rich in sucrose), non-sticky (hands and packaging) and have a great faculty of conservation. Typical examples of these cultivars are *Kentichi* (Tunisia), *Degla Beydha* (Algeria) and *Jihel* (Morocco). These cultivars are still popular with the rural population and are also exported to some African countries such as Mali, Niger and Senegal in Tunisia and Algeria [21].

6 Dates Characterization

Dates characterization is mainly based on a morphological, physicochemical and organoleptic evaluation. There are hundreds of named cultivars of *Phoenix dactylifera* date palms, each of these cultivars produces delicious dates with distinct differences in flavor, sweetness, moisture content, and size. Based on the shape and the organoleptic properties of the fruits, there are more than 600 date cultivars all over the world [1, 9] which are influenced by environmental conditions [22]. More than 200 cultivars of dates are grown in the 29,000 hectares of Tunisian palm groves. In addition to the common date cultivars, Tunisia produces high quality cultivars called dessert dates; the best known is "*Deglet Nour*".

According to the [23], the minimum characteristics of an acceptable quality of date fruits are as follows:

- Intact: dates are excluded when the skin has been crushed, torn, revealing the kernel;
- Healthy: produce affected by rotting or deterioration such as to make it unfit for consumption is excluded;
- Clean: practically free from any visible foreign matter; the coating ingredients are excluded;
- Free of live parasites, regardless of stage of development;
- Free from visible parasites attacking the naked eye, including dead insects and / or mites and their residues or faeces;
- Free of mold filaments visible to the naked eye;
- Free from fermentation;
- Free of immature fruit;
- Free of abnormal external moisture;
- Free of foreign smell and/or taste.

6.1 Physiological Characterization

The physiological characteristics of the dates can vary enormously depending on the stage of maturity. [24] indicated that date is a berry, generally with elongated shape. Its dimensions are extremely variable from 1.5 to 8 cm in length and weighing from 2 to 20 g. Its color ranges from yellowish-white to dark-brown, almost black, to amber, red, and brown. The date contains a single seed called "kernel". The edible part of the date is called "flesh" or "pulp" and consists of the mesocarp whose consistency can vary according to the cultivars, the climate as well as the period of maturation: soft (31% water), half soft such as *Deglet Nour* (18% water) and dry such as *Kentichi* (12% water).

The inedible portion is formed by the seed (the core or kernel) having a hard consistency and represents 10% to 30% of the weight of the date. According to [25], a date is said to be of acceptable physiological quality, when it presents no abnormality and no damage, a weight $\geq$ 6 g, a pulp weight $\geq$ 5 g and a length $\geq$ 3.5 cm. The *DegletNour* date is a soft and excellent half date. Its dimensions, according to [24] are as follows: an average weight of 12 g; average length of 6 cm and an average diameter of 1.8 cm. It presents a smooth core, small 0.8–3 cm and pointed at both ends. The ventral groove is shallow, the micropyle is central. The *DegletNour* date is tapered, ovoid, slightly flattened on the perianth side. At the Tmar stage, the date becomes shaded, with a smooth and shiny epicarp. The mesocarp is thin with fibrous texture. *Deglet Nour* is the queen of all dates. Marketed since 1870, this variety is known as "the date of brilliant light" for its translucent blonde color, the softness of its appearance and the elegance of its shape. It is almost transparent.

It is the most popular variety in the world for its superior quality and unique honey taste. It is the only variety that can be marketed naturally in the form of twigs. The *Deglet Nour* variety is mainly produced in Kebili and Tozeur. *Allig* is a long form date, particularly tasty, picked in November. Its color is dark mahogany, its flesh is abundant, soft and its texture is semi-soft. The *Allig* variety is produced in Tozeur and Kebili and to a lesser extent in Gabes and Gafsa. *Khouet Allig* is a date palm fruit with a texture, color and taste similar to those of the *Allig* variety, hence its name, but slightly thinner and less sweet. *Khouat Allig* is produced essentially in Tozeur (90%); the rest of the production comes from the oases of Kebili. *Kenta* has a light golden color and a seductive appearance; this date variety has an early maturity. It is less sweet than all other cultivars and has a semi-dry texture. Kenta is the main product of the coastal oases of Gabes, but it's also produced in Kebili [13].

6.2 Dates: A Nourishing Fruit with an Exceptional Composition

[26] were among the first scientists who elucidated the chemical composition of dates. In fact, they cited that the date contains many benefits for the human body. It is very rich in potassium and iron; it contains a lot of vitamins, minerals, and carbohydrates that makes it an energetic fruit, and a key food source to facilitate muscular effort. It is therefore an interesting ally to consume for athletes. It also contains a high level of sugars (glucose, sucrose, and fructose). Its very high fiber content facilitates intestinal transit. As an important source of antioxidants, it would also reduce cholesterol levels, and the risk of certain cardiovascular diseases. In fact, [27] reported that date fruits are rich in polyphenols, anthocyanins, carotenoids, tannins, procyanidins, sterols, flavonols, flavones, anthocyanidins, isoflavones, phytoestrogens phenolic acids andcinnamic acid.

The little work done on the composition of Tunisian dates confirms their nutritional richness. [28–30] studied the different chemical groups present in the pulp of Tunisian date cultivars *DegletNour, Khouet Kenta, Kentichi* and *Allig*. Results showed the richness of these cultivars in various antioxidant chemical groups such as iridoids, tannins, saponisids, coumarins, flavonoïds, phenolic acids and carotenoids. Phenolic acids and carotenoids represent the major antioxidants components. The caffeic, vanillic, syringic, gallic and p-coumaric, ferulic and the p-hydroxybenzoic acid constitute the major acids present in most of these cultivars. Results demonstrated, that all date cultivars contained carotenoids pigments, in which β-carotene is the major carotenoid revealed by thin layer chromatography. [31] affirmedthat date palm fruit may serve as a good source of different active compounds and could potentially prevent many diseases.

[32] studied the chemical composition of 15 date's cultivars grown in Tunisian coastal oases (*Ammari, Bouhattam, Eguiwa, Feliane, Ftimi, Garn Gazel, Halwai Abiadh, Kenta, Korkobbi, Ksebba, Lemsi, Mattata, Mermella, Rochdi* and

Smiti). They found that dates of the different cultivars are soft and semi-soft. They are rich in reducing sugars in comparison with continental oases dates, in particular *Deglet Nour*, except the cultivar *Garn Gazel* for which reducing sugars are almost equal to sucrose. This characteristic is almost specific to littoral dates. These dates are easily assimilated which makes them interesting for transformation. The total nitrogen content varies between 0.93 and 4.06%. These littoral cultivars have shown to be rich in K and P and less rich in Ca and Na.

This richness was confirmed by [33], who focused on the physicochemical characterization and sensory profile of seven dates cultivars *(Deglet Nour, Allig, Mnekher, Angou, Horra, Kentichi, Hamra)* collected from southern Tunisia (Dgueche and Gabes). Morphological characteristics were studied based on the length and the diameter measurements, besides pulp and pit weights. The physicochemical analysis takes into consideration the values of total and reducing sugars, the water content, the ash percentage, the acidity (pH), the volatile acid, the color and the texture. The sensory profile showed that each cultivar has unique and specific characteristics (color, texture and taste).

Owing to their richness in several secondary metabolites, dates fruits exhibited many pharmacological activities in some diseases control as mentioned by [34, 35] such as cardiovascular disease, constipation [36], antimicrobial, antitumor, anti-inflammatory, antidiabetic [37], nephroprotective, sex hormone modulator. [14] focused on the evaluation of the chemical composition, functional properties [38] and antioxidant activity of fibers obtained from the solid fraction of Tunisian secondary date varieties (*Phoenix dactylifera L.*) by hydrothermal treatments. On their side, [39] studied the chemical composition of eleven Tunisian dates' cultivars, collected from Gabes and the island of Djerba. The cultivars *Ammari, Baht, Bekrari, Bouhattem, Eguiwa, Garn Ghzel, Halway, Kenta, Korkbi, Lemsi, Mermella, Nefzaoui, Smitti and Rotbi* are marginalized. However they could be a good source of high nutritional quality juice, with a significant antioxidant power. This study revealed that the obtained product is also rich in reducing sugar with high energy content as well as in mineral elements mainly potassium. [40] were also interested in the physicochemical characterization of seven Tunisian dates' cultivars grown in Gabes (*Eguiwa, Bedh Hamam, Bouhattem, Deglet Nour, Garn Ghzel, Hammouri* and *Rotbi*). Their work has shown that the fruits of date cultivars are rich in sugar (37.75–67.34% FW) and that only the variety *Deglet Nour* contains sucrose (non-reducing sugar). These date fruits present a low amount of fat (0.142–0.24% FW) and protein (1.19–2.89% FW). As for the mineral content, they are very important sources of potassium followed by several other minerals as calcium, magnesium, sodium, iron, zinc and manganese. [41] reported in their review that date palm fruit is rich in carbohydrates, dietary fibers, proteins, minerals and vitamin B complex, such as thiamine (B1), riboflavin (B2), niacin (B3), pantothenic (B5), pyridoxine (B6) and folate (B9). Besides, they indicated that date fruits are rich in minerals mainly calcium, iron, magnesium, selenium, copper, phosphorus, potassium, zinc, sulfur, cobalt, fluorine, manganese and boron.

6.3 Sensory Characterization

We indicated in one of our earlier works on Tunisian dates that sensory analysis is an essential step in chemical analysis for defining the characteristics and value of food products [33]. However, the sensory analysis for dates is particularly difficult because of the sweet taste of the product, that's why the relations between the preference of Tunisian consumers and sensory properties of dates have not been established in the scientific literature. Some studies have focused on morphology characterization of dates or date products [2] and others on physicochemical and biochemical identification [42, 43], but few have considered the sensory evaluation of dates [44, 45]. Sensory analysis is considered an important technique to determine the quality of the product. It includes a set of techniques for measuring human responses following food tasting [46]. The study of [33] aimed to determine the appearance, smell, flavor and texture of food products. Sensory evaluation requires a tasting panel. Seven dates cultivars were characterized based on several descriptors as color, tactile texture, mouth texture, stickiness, astringency, sweetness, bitterness and global appearance. Consumers from southern and northern Tunisia preferred respectively *Deglet Nour, Alig, Mnekher, Horra, Hamra, Kintichi* and *Angoua.* Some significant differences were observed for these seven cultivars following the results of the sensory analysis. For example, each cultivar has its own color: Kintichi is qualified as the clearest one but Alig as the darkest one. In addition, no significant difference was observed for acidity and sandy texture for all cultivars. This organoleptic assessment, with its analytical and hedonic aspects, revealed that the Tunisian consumer is attracted by sweet cultivars with the best texture in the mouth and the best appearance. This investigation concluded that the Mnekher cultivar, which is a rare and declassified date, covers 50% of potential preferences. Other studies found that sugars play an important role in determining the consistency of dates. Indeed, reducing sugars characterize dates of soft consistency; sucrose characterizes dry dates [47].

7 Dates Cultivars Valorization

According to [15], the dates constitute a product of high added value which is valorized in several fields such as food industries, animal feed, energy production and carpentry.

7.1 Valorization in Food Industries

[6] reported that date cultivars are an underexploited natural product which needs more interest from scientists although it has been valued particularly in food industries thanks to its richness in secondary metabolites especially fibers and antioxydants. [15] cited some products manufactured from dates such as pasta of dates, date flours, stuffed dates, coated dates, date syrup, drinks, industrial vinegar, yeast and date sugar. Date molasses are made from dates cooked in water then filtered to finally be pressed to extract a juice. This juice is concentrated by cooking over low heat until a colored and syrupy liquid is obtained. The valorization of date sorting gap is the elaboration of a drink after clarification by enzymatic treatment and microfiltration. A survey of Tunisian farmers, artisans, workers in the date sector showed that these fruits are transformed in different products. After grinding the pitted fruit, the date's pasta is obtained. After roasting and grinding date kernel, the coffee is generated (Houyem coffee). When removing the kernel, cutting and baking the date paste, we get jam. The filtration and the concentration of juice dates provide us with "*Robb*", which is a high energetic food rich in saccharides and carbohydrates [48], whereas the waste of the filtrate is transformed into vinegar if the fermentation is acetic, and in industrial or surgical alcohol following an alcoholic fermentation and distillation. These transformations are mainly applied for *Allig* and *Deglet Nour* cultivars. However, *Kentichi*, is sun-dried and crushed to date flour. [49] indicated that date palm fruits are traditionally used to prepare a range of products such as date juice concentrates (spread, syrup, liquid sugar), fermented date products (wine, alcohol, vinegar and organic acids) and date paste for different uses (bakery and confectionery) in addition to their direct consumption. They also reported that date processing industries manufacture the same traditional products in addition to the extraction of date pectin [50], dietary fiber used as a thickening or gelling agent in processed foods, i.e. confectionery, jams, jellies, soft cheeses, yogurts, etc. The extraction of date juice and date syrup was also studied by several researchers [45, 51, 52]. In addition to that, [53] indicated that some seeds date cultivars (DegletNour, Allig and Belah) were used as source of lipid extraction. Besides, [38] demonstrated that not only date fruit are of great interest, but also male date palm flowers are endowed with some functional properties which allow them to be incorporated in food because they are nutritional products with conservation characteristics.

7.2 Valorization of Date Sorting Gaps by Drying to Obtain a Powder for Animal Feed

The sorting gap of the most widespread dates in Tunisia is valorized (nucleus + pulp) by application of drying process. The product concerned is flour for animal feed. The physicochemical composition of the dried date powders at different temperatures shows that the latter are rich in soluble sugars, polysaccharides, high levels of potassium and magnesium. However, the powder has low levels of protein, crude cellulose and fat [15].

7.3 Valorization in Cosmetics and Artisanal Products

The retentate of date's juice filtration as well as the crushed Kernel can be valorized in cosmetics following the extraction of the oils, and the formulation of soap. After carbonization, date kernels give 100% natural Khol which is used as make up for the eyes. Cornafs, lifes and stipe are valued in various craft products such as baskets, jewelry boxes, hand bag, lampshade.All these informations were obtained from a direct survey to artisans.

7.4 Energy Production

The main valorization of date waste for energy purposes is compost, biodiesel and bioethanol production as described by [53]. In Tunisia, the date packaging units generate significant amounts of waste from sorting differences. This biomass, considered as waste with a strong impact on the environment, can be transformed into a high value product. The valorization of by-products of the date industry in biofuel is part of an economic and environmental approach. Because of its richness in fermentable sugars (about 75%), date waste can be transformed by biotechnological processes into biofuel or bioethanol.

7.5 Manufacture of Date Palm wood and Furniture with Liquid Wood

Regarding the manufacture of furniture with the technique of liquid wood there is only one unit which is called "Royal Mondial" located in Tozeur in southern Tunisia. The raw material is very abundant because it's waste of palm that will be crushed and transformed into several products like wall coverings, insulators, kitchen furniture, tables and chairs [15].

8 Conclusion

This investigation highlights the importance of date palm tree all over the world and in Tunisia, whether commercially or nutritionally, as a source of certain nutrients (vitamins, minerals, amino acids, proteins, non-reducing sugars, water, fiber …). Date is a ployphenol reservoir with high antioxidant power allowing it to fight several diseases. This chapter also provides an overview on the value of date palm fruit (*Phoenix dactylifera* L.) which has been known over centuries, mainly the originality and the valorisation of Tunisian dates.

The incorporation of dates into food has helped to promote new products valued by consumers. Also, it is interesting to propose new ways of valuing sorting gaps and declassed cultivars in order to minimize losses and expand the range of byproducts of dates. This chapter also presents the results of several date co-products that have been developed and validated by sensory analyzes. This study aims to show the different virtues of this noble fruit as well as possible avenues for its valorisation whether in an artisanal or even industrial way. It is a way to enhance the Tunisian date fruits on which we propose a study to introduce the Label Protected Designation of Origin.

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Ecological Distribution, Phytochemistry and Biological Properties of *Rosa* Species in Tunisia

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Abstract *Rosa* species, classified as Medicinal and Aromatic Plants, are widely distributed in the Northern and Central of Tunisia. The investigation has concerned eight *Rosa* species distributed in the north area of Tunisian dorsal. This review aims to describe the Rosa species discrimination based on their geographic repartition, edaphic preferences, bioclimatic situations, plant communities, phytochemical compositions and biological activities. It has been shown that these species require wet conditions and they grow in zones where the rainfall is more than 400 mm.yr^{-1} and they are glycophyte species. *Rosa* species, belonging to the Section *Caninae,* are reported to have several preferences of climatic and edaphic conditions. For *Synstylae* species, *Rosa moschata* was cultivated in sandy and equilibrate soils with semi-arid or subhumid climate (Zaghouan, Nabeul, Bizerte and Testour regions). However, *Rosa sempervirens* was disseminated in a large geographical area giving it the most elastic species. The floristic richness was more important in *R. canina, R. sempervirens* and *Rosa moschata* associations as compared to those of *Rosa agrestis* and *R. micrantha*; these species are more resistant to arid climate when the rainfall is less than 400 mm.yr^{-1}. Finally, it was reported that *Rosa* species exhibit several

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biological activities and their phytochemical richness was influenced by species and organs variation, extraction protocols and environmental conditions.

Keywords *Rosa* species · Tunisia · Ecology · Phytochemical richness · Activity

1 Introduction

The Rosaceae is a cosmopolitan family which is distributed especially in temperate and sub tropical regions of Northern hemisphere [1]. The *Rosa* family included about 3300 species which are divided into about a hundred genera [2, 3]. *Rosa* sp belongs to the Rosales order. This genus is illustrated by great diversity and different ploidy levels [4–6].

North Africa is one of the original birth places of the extension of rosehip. In Tunisia, those populations were studied for the first time by Pottier- Alapetite in 1979 [7] who founded eight species: *Rosa gallica* L., *R. agrestis* Savi., *R. sicula* Tratt., *R. sempervirens* L., *R. stylosa* Desv., *R. micrantha* Sm., *R. moschata* Hermm. and *R. canina* L. [7]. Since, prospecting and studies have been carried out by researchers at different scale regions. In the Kroumirie region, *Rosa canina* and *R. sempervirens* were studied by Ghazghazi-Albouchi [1]. The areas surveyed by Ben Cheikh Affene [3] are North East (Bizerte and Zaghouan), North West (Jendouba, Beja, Seliana) and Central Tunisia (Kairouan); the species studied are *R. agrestis*, *R. micrantha*, *R. canina,* and *R. sempervirens*. Ben Cheikh-Affene [3] showed that Tunisian population Wild roses subdivided into two sections: *Synstylae* and *Caninae* and she identified seven separated taxa: three for *Synstylae* and four for *Caninae* section. Ouerghemmi [8] studied Wild roses in five regions: Kroumirie, Mogod, Bizerte, Nabeul, and Zaghouan and three species were investigated: *R. canina, R. sempervirens*, and *R. moschata*. The *Rosa* species need humid climate, and they are growing in different soil classes [9, 10] rich in organic matter; for this reason, these species are distributed in Northern and Central Tunisia. The biotic, abiotic parameters, and localization of these species were passed in review in this study.

Rosa species have used for several purposes. They are considered as aromatic and medicinal plants with various therapeutic virtues thanks to their very rich organs on bioactive compounds. Some species like *Rosa moschata* Herrm. are cultivated for cosmetic and culinary uses. In Tunisia, the cultivated areas evolved from 2 hectares in 2002 to 34 hectares in 2012.

In traditional medicine, tea obtained from dried bud and petal roses was used as source of antioxidants due to their important polyphenol and flavonoid contents [11]. Rosehips are traditionally consumed as tea, puree or jam preparations and they present a nutritional healthy foods [12, 13]. *R. canina* and *R. sempervirens* rosehips include important levels of vitamin C, polyphenols and flavonoids and reveal high antioxidant, anti-inflammatory and cytotoxic effects [12–19]. Leaves of *R. sempervirens* showed also antioxidant and antifungal activities [20]. In traditional or folk medicine, roses were also used for the treatment of osteoarthritis and the rheumatoid arthritis due to the anti-inflammatory activities of their flavonoids, triterpenoids and phytosterols [21]. Hips of Rosa canina possess hepaprotective properties and are consumed for the prevention of diabete deseases [22].

For the majority of the plant kingdom, qualitative and quantitative phytochemical compositions and their corresponding activities, were generally influenced by species and organ variations, regional origins, solvent extraction, mechanical treatement and many other biotic and abiotic factors [8, 18, 23].

2 Taxonomic Characters of *Rosa* Species in Tunisia

The taxonomy of Wild Roses is very complicated [6] because of its biological characters, reproduction mode and geographic localization. The morphologic and anatomic characters are not very specific and discriminatory between different species [6, 24]. These plants are belonging to the genus *Rosa* which is divided into four subgenus: *Hulthemia*, *Hesperhodos*, *Platyrhodon* and *Rosa* [6, 25]. The last subgenus (*Rosa*) is also divided into ten sections: *Pimpinellifoliae*, *Gallicanae*, *Caninae*, *Carolinae*, *Rosa* ou *Cinnamoneae*, *Synstylae*, *Indicae*, *Banksianae*, *Laevigatae* and *Bracteatae* [6, 25].

According to Wissemann [6], the section *Caninae* is divided into six subsections: *Trachyphyllae*, *Rubrifoliae*, *Vestitae*, *Rubigineae*, *Tomentellae* and *Caninae.*

The *Rosa* genus is represented by climbing and thorny shrubs characterized by alternate leaves which are frequently composed and rarely simple. The flowers are terminal or arranged in corymbs type five sometimes four and contained many stamens. The carpels end with long styles that are gathered or agglutinated in the receptacle [6, 7].

The following described *Rosa* species are those indicated in the Tunisian flora [7] and/or the species investigated by Tunisian researchers [1, 3, 8].

2.1 Rosa Dumetorum Thuil.

Ben Cheikh-Affene et al. [27] studied morphometric and taxonomic identification of *R. dumetorum* Thuil. This *Rosa* species has localized seliana. *R. dumetorum* Thuil. belongs to the section *Caninae* and the subsection *Caninae* [6]. This species is characterized by 7 leaflet-leaves pubescent in both sides or only the rachis, short pedicel, long and smooth receptacle, glabrous reflex sepals lobed by many appendix and deciduous after anthesis. Flowers or R. dumetorum are white to pinkish [6, 26].

2.2 *Rosa Pomifera* L.

Rosa pomifera L. is a compact and low shrub belonging to the section *Caninae* subsection *Vestitae* [6]. This plant is characterized by short erct sepals, glandular and hairy leaflets on both sides, straight or curved spines, pink-red to white nail flowers [6]. *R. pomifera* L was spontaneously investigated in Kairouan in the central region of Tunisia [27].

2.3 *Rosa Rubigenosa* L.

Rosa rubigenosa L. belongs to the section *Caninae* subsection *Rubigineae*. Its principale characteristics are glandular glabrous or hairy leaflets, hooked spines, gland-tipped bristles, pinnate and moderately deciduous sepals, pinkish-white flowers [6]. In Tunisia, this species was prospected in the regions of Beja and Kairouan [26, 27].

2.4 *Rosa Canina* L.

Rosa canina L. is a strictly *Caninae* species (section *Caninae*, subsection *Caninae*) [6]. The imparipinnate leaves with basipetal development have five to seven leaflets ovoid or septic and pointed shape for *R. canina* (Fig. 1). They are caduc, semi persistent, or persistent in alternative disposition [3, 8, 28]. The flowers are pale pink or white, solitary, or grouped in corymbs at the ends of twigs [7]. The sepalsare reflected after anthesis and quickly become obsolete. At maturity, the receptacle turns red and

Fig. 1 Photos of *Rosa canina* flowering (on left part) and shrubs (on right side) grown in Jendouba region, Northwest of Tunisia. *Personal photos taken in-situ during the Rosa exploration in the region of El Feija (Ouerghemmi, 2012)*

Fig. 2 Photos of *Rosa moschata* flowering (on left part) and shrubs (on right side) grown in Nabeul region Northest of Tunisia. *Personal photos taken in-situ during the Rosa exploration in the region of Nabeul (Ouerghemmi, 2009)*

becomes pulpy to give the rose hip. This rose hip is elongated egg-shaped and contains achenes with hard pericarp and covered with stiff hairstyles. The fruit harvest lasts between August and October. Pottier-Alapetiete [7] has founded four subspecies: *R. canina ssp.obtisifolia*, *R. canina ssp. pouzini*, *R. canina ssp.dumetorum*, *R. canina ssp.vulgaris*.

2.5 Rosa Moschata Herrm.

Rosa moschata Herrm. belongs to the section *Synstylae* [6]. Plants of this section are characterized by column-agglutinated and long styles as stamens [6, 26]. *R. moschata* is confused with *Rosa brunonui*; it is a shrub with long branches, climbing to reach meters and carrying few prickles (Fig. 2). The leaves are leathery, persistent, and composed of seven leaflets. The flowers are grouped in corymbs, and the sepals are lanceolate and elongated [7].

2.6 Rosa Sempervirens L.

The port plant of *Rosa sempervirens* L. is similar to that of *R. moschata* (Fig. 3). This species is a climbing shrub with slender and long branches [26]. *R. sempervirens* belongs to the section *Synstylae* and their leaves are composed of five leaflets completely hairless. The inflorescence is arranged in corymb, and the sepals are abruptly terminated in point [6, 7, 26].

According to Ben Cheikh-Affene et al. [26], three varieties of *R. sempervirens* were investigated in Northern of Tunisia:

Fig. 3 Photos of *Rosa sempervirens* flowers(on right part) and shrubs (on left side) grown in Jendouba region Northwest of Tunisia. *Personal photos taken in-situ during the Rosa exploration in the Northwest region of Tunisia (Ouerghemmi, 2014)*

- *Rosa sempervirens* var. *genuina,* with glandular floral pedicel, receptacle and calyx;
- *Rosa sempervirens var. submoshata*, with many appendix in sepals;
- *Rosa sempervirens var. prostrate.* The name was attributed to the variety according to its prostrate habit.

2.7 Rosa Gallica L.

It was a short shrub whose height varies from 40 cm to 1.5 m. This species grows in hedgerows and rarely in wood, and it is subspontaneous near gardens. The flowers are bright pink, red or velvety red. The flowering date is in June-July. The prods are unequal some are strong, straight or slightly arched. The leaves are composed of five leaflets sometimes only three. These leaflets are leathery or rather thick with veins protruding on the underside. The mature fruits are red, ovoid, or almost globular [7]. *Rosa gallica* L. belongs to the section *Gallicanae* [6].

2.8 Rosa Sicula Tratt.

The plants of this species are low shrubs belonging to the section *Caninae*, with a height of 30 cm. Its leaflets are lined with glandular, sometimes round, oval cilia. The prods are unequal, close together; some are straight, others are crooked or arched.The sepals are more or less glandular standing and persistent after flowering. The flowers are pink [6, 7].

2.9 *Rosa Agrestis* Savi.

Rosa Agrestis Savi grows in woody land and hedgerows, especially in mountain zones [7]. This species belongs to the section *Caninae* subsection *Rubigineae* [6]. The flowers are white or pale pink. The leaflets are pubescent and glandular in under side and longer than 2 cm. The prods are unequal more or less spaced. Its leaflets are hairy or not oval or elongated oval. The sepals are non-glandular inverted and falling after flowering. The fruits become fleshy well before being mature, and they are usually smooth [7, 26].

2.10 *Rosa Stylosa* Desv.

Rosa stylosa Desv. is owned to the section *Caninae* subsection *Caninae* [6]. Those roses are characterized by long styles. The shrubs can reach several meters in height found in hedges, bushes, woods or hillsides. The prods are crochus or curved in semi-circle. The leaves are composed of 5–7 leaflets, formed like a flame of a candle, without hair or covered by little hairs with small smell glandular. Sepals are reflexed, without glands on the back and deciduous after the anthesis. The styles are agglutinated during flowering and form together as a sort of salient column. Flowers color is pinkish to white [6, 7].

2.11 *Rosa Micrantha* Sm.

Rosa micrantha Sm. belongs to the subsection *Rubigineae* of the section *Caninae* [6]. This species is a shrub whose high varies from 30 cm to 2 m. The leaflets are contoured elliptical, obtuse at the top and they are pubescent and glandular on both sides, copiously pinnate. The prods are crochus or arched.The sepals are, reflexed, glandular, deciduous and overturned outside after flowering. Hips are usually small. The flowers are pink, rarely white [6, 7, 26].

3 Prospection and Localization of Different *Rosa* Species Inventoried in Tunisia

Several prospections have been carried out by researchers for determinate the expansion of different species of the genus *Rosa* in Tunisia. It has been found that spontaneous *Rosa sp* can only occur in areas with rainfall greater than 400 mm. yr^{-1} or in the watercourse when the climate is dry.The rosehip is a glycophyte, and it does not

Fig. 4 Photos of *Rosa* × *alba* shrubs at the flowering stage grown in Jendouba region Northwest of Tunisia. *Personal photos taken in-situ during the Rosa exploration in the region of Aïn Drahem in Northwest of Tunisia (Ouerghemmi, 2013)*

tolerate water loaded with NaCl. The increase in salinity causes the reduction of the biomass from 30 mM of NaCl.

Fifty-eight accessions of *Rosa canina* were recorded in 53 sites in Jendouba, two in Siliana and one in each of the Beja, Zaghouan and Bizerte regions. One hundred twenty-nine accessions of *Rosa sempervirens* were identified in 66 sites in Jendouba, 23 in Béja, 23 in Bizerte, 8 in Zaghouan 5 in Nabeul, and one site at Siliana.For *Rosa moschata*, 44 accessions were found, spread over the following regions: 12 sites in Bizerte 15 sites in Nabeul, 13 in Zaghouan, 4 in Beja. *Rosa micrantha* is present in two sites at Kairouan and Siliana regions, and*Rosa agrestis* is signalized in Beja and Kairouan regions. At last, *Rosa* x *alba* (Fig. 4) is identified in one site at Jenbouba region. A total of 236 sites were investigated in northern and central Tunisia (Fig. 5).

The rosehip surveys are carried out during two periods: in the spring between April and May corresponding to the flowering period and between August and October, a fruiting period of *Rosa sp*. It is not easy to distinguish roses without their flowers.

Rosa canina is found in areas with altitudes ranging from 650 to 1100 m. This species is located in the highest altitude sites compared to other species. *Rosa moschata*has a wider range than *Rosa canina*; This species is found in the spontaneous or cultivated state with altitudes ranging from 12 to 261 m. *Rosa sempervirens*is exclusively spontaneous. This species is located in the majority of the regions visited; if rainfall is low, *R. sempervirens* colonizes thewater-courses. The altitudes range from 5 to 659 m. *Rosa* × *alba* (Fig. 4) is located in one site at Jendouba with an altitude 675 m. The stations of *Rosa micrantha* are situated in Siliana and Kairouan at 490 and 264 m of altitudes, respectively. The *Rosa agrestis* sites are situated in Beja and Kairouan at 228 and 264 m, respectively.These last three species are less widespread than the other obovementioned species.

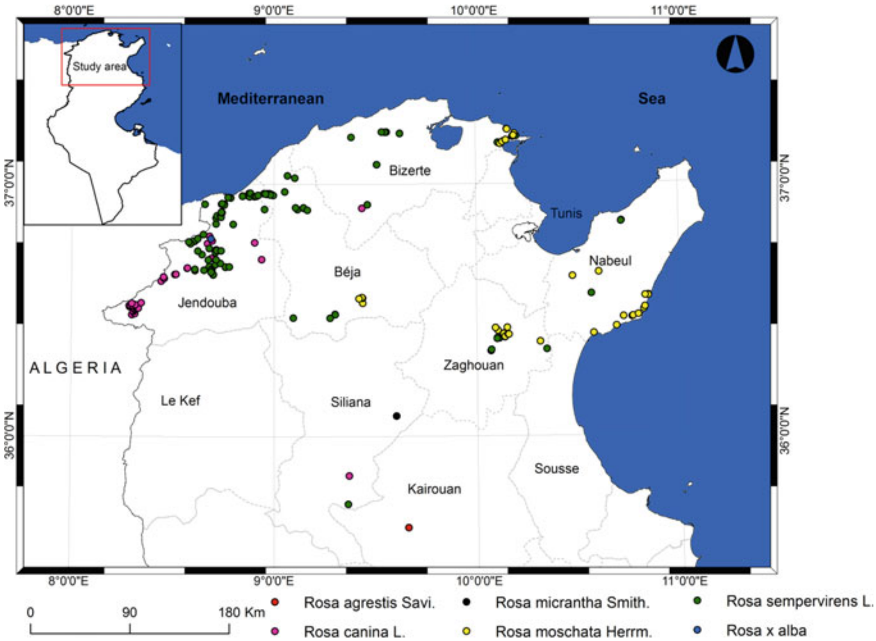

Fig. 5 Localization of the distribution sites of five *Rosa* species and *Rosa* × *alba* hybrid species (one site) at different regions of Northern and Central Tunisia according to their GPS coordinates. The boundaries of the region areas where *Rosa* species are distributed are indicated in the map. The species sites are indicated by a circle and the color inside the circle differs from one species to another

4 Ecological Characteristics of Some Species of *Rosa* in Tunisia

The investigation concerned five *Rosa* species, among the eight inventoried in Tunisia. These species are distributed in northern and central Tunisia. The studied species are:*Rosa micrantha* Sm., *Rosa agrestis* Savi, *Rosa sempervirens* L., *Rosa moschata* Herrm., *Rosa canina* L. The ecological studies and the geographical distribution of these species will be discussed. The Studies of the associated species in the different sites, soils, and biclimates of the rose hips will be detailed in this work. Chemical characters and biological activities will be reviewed.

4.1 Edaphic Characteristics of Species Distribution Areas of Rosa Sp. in Northern and Central Tunisia

Rosa species are distributed in different regions of northern and Central Tunisia. The localities are characterized by different types of soils.

In the Kroumirie region, the soils have AC or ABC soil profiles [9, 29]. According to the French soil classification, there is no A_2 soil horizon under A_1. This one is thick, which can reach 20 cmwith a very dark color and a grumulousstructure. The thickness of horizon B can reach 30 cm andcontains less humus than horizon $A_{1,}$ and the depth of these soils does not exceed 60 cm. These soils were formed on very clayey rocks. The organic matter turned into humus type mull which the mineralization rate is quite fast to fast depending on the nature of the vegetation [30], and the C/N rate varies between 12 and 15. The pH of these soils is slightly acidic. The presence of high proportions of clay and silt gives a fine texture where the drainage is poor, and the porosity is low. The species found in these sites are *R. canina* and *R. sempervirens.*

On Mediterranean shores from Tabarka to Nabeul, the class of poorly evolved soils of non-climax origin covers those zones. These soils are of modal contribution on Aeolian sands [29, 30]. This area is covered by *R. sempervirens* and *R. moschata.* Those species are mixed with *Quercus coccifera* which occupied the ancient dune soils.The humus is distributed over the entire profile.The shrubs of kermes oak, which the thickness is 50 cm for two horizons, are few humic. The soils have a neutral pH but at a deeper depth, the pH reach of 8.4 where the limestone is very abundant [9, 30]. This area is covered by *R. sempervirens* and *R. moschata.*

In Zaghouan and Bizerte governorates, the calciferous and isohumic soils are distinguished; at Zaghouan, the soils are rendziniform and brown calcareous and vertisols accumulated on marl or alluvium in Bizerte. The brown calcareous soils have anindividualized profile A(B)C. The C/N ratio is less than 15. This soil is characterizedby a balanced texture horizon resting on the calcareous crust. The texture is sandy-clay or clay-silty, and the limestone content varies according to the sites.These soils are subject to high water erosion due to the nature of the original material; in fact, the low stability silt favorite this erosion. The modal vertisols have a blown horizon with large slits of 5 to 7 cm recessesduring the summer [9, 29]. The soils of Bizerte formed in the depressions are covered during the dry period following the rainy season with a layer of polyhedral elements of 1 to 2 mm giving to the superficial horizon are covered a high porosity. These soil units are found in depressions marked by lagoon formations. The species inventoried in this zone are*R.moschata*, *R. sempervirens,*and*R.canina*only in Khanguet Oued Touil in Joumine-Bizerte. The humus rendzines are located in Jebel Serj of Siliana region where *R. canina* is found [9].

In central Tunisia, the soils are classified as “calcimorphic soils, lithosols, and regosols” [9, 29]. The (B) horizon has a dull polyhedral structure. Around the thalwegs and depressions, a slight hydromorphy gives the soil a prismaticstructure. The horizon Ahas the same characteristics than the rendzines. The pH of those soils are more than 8, which are limestone, and the texture is silty clay. Two species were founded: *Rosa agrestis*, and *R. micrantha*.

4.2 Bioclimatic Characteristics of Northern and Central Tunisia Occupated by Rosa Species

Tunisia is characterized by great variability in vegetation and genetic resources. This is due to it environmental diversity characterized by three different climatic zones: the northern Mediterranean, the central steppe and the southern disert bioclimate zones [31]. *Rosa* species are investigated in the north and centre of Tunisia.

Rosa canina is distributed in three regions of Kroumirie, Bizerte, and Zaghouan. El Feija region (Kroumirie) is characterized by 1217 mm.yr^{-1} rainfall mean valueover a 76-year observation period [30, 32]. The mean temperature is 14.3 °C over an observation period of 60 years. This region has a humid bioclimatic stage with cool winters according to Emberger's Mediterranean bioclimate classification, this species was determined in some localities of Bizerte and Zaghouan, which the mean rainfall is 550 mm.yr^{-1} and temperature 18 °C; those zones have subhumid bioclimate with a mild winter variant. The mean of rainfall of Djebel Bargou (Siliana gouvernorate) is 450 mm.yr^{-1} (1901–1980) [29] and the average of temperature is 18 °C. The bioclimate stage is subhumid variant temperate winters.

Rosa moschata grows spontaneously or by culture, especially in Zaghouan. Its distribution is more extensive than *R. canina.* It expands in the regions of Nabeul, Bizerte, and Zaghouan. The mean of rainfall of Zaghouan is 501 mm.yr^{-1} over an observation period of 62 years and temperature mean 18 °C over 45 years giving anupper semi-arid bioclimate with mild winters [30, 32]. Bizerte presents a climate characterized by a value of rainfall mean 530 mm.yr^{-1} over 51 years and a mean temperature of 18.6 °C. Those localities have a subhumid bioclimate with a hot winter variant. Nabeul records the lowest rainfall with an average of 424 mm.yr^{-1} (rainy period of 48 years) and an average of temperature 18.5 °C, and it belongs to superior semi-arid bioclimate with hot winters [30, 32].

Rosa sempervirens is a spontaneous plant but has a larger geographical area than the two species*R. canina*and *R. moschata.* Indeed, it is located in the northwestern regions of Nefza to Fernana via Tabarka, Ain Draham and Ben Metir and from Ain Draham to Hammem Bourguiba. The rainfall in these areas ranges from 1572 to 740 mm.yr^{-1} to Ain Draham and Fernana (respectively) over periods of 80 and 13 years, respectively [30, 32]. The temperatures vary between 14.9 and 17.4 °C in the same regions. The bioclimates are variable from suhumid to humid with the upper and lower sub stages.The bioclimatic variants pass warm and mild winters to those of temperate winter then cool [30, 32]. In Nabeul and Zaghouan regions, this species is distributed at the base of the southern slope of Djebel Abderrahmane (Nabeul) and at a certain altitude of Djebel Zaghouan (northwestern slope). The rainfall ranges from 550 to 610 mm.yr^{-1}and average temperatures of 18 to 18.5°

C (Zaghouan andNabeul, respectively). The bioclimatic stage is subhumid in both regions and two variants hot winters in Nabeul and sweet in Zaghouan.This species is less demanding, and it is suitable for almost all climatic and edaphic environments.

Rosaagrestis, and *R. micrantha,* these two species have been reported in central Tunisia and locally in Haffouz (Kairouan). *R. micrantha* also covers Djebel Bargou (Siliana gouvernorate). The mean of rainfall of Kairouan is 320 mm.yr^{-1} (1901–1980) [29] and 450 mm.yr^{-1} in Siliana and the average temperature is 18 °C in these two regions. The bioclimate stages are subhumid with variant temperate winters in Djebel Bargou and upper arid with bioclimatic variant temperate in Haffouz.The geographical extension of these two species is less restricted than the other species. Their localization shows that they are more resistant to the continental sites.

4.3 The Plant Communities of Rosa Sp. in Tunisia

The vegetation of *Rosa canina* stations in Kroumirie region belongs to the association of *Cytiso Quercetum suberis* Br. Bl. 1953. The altitude varies from 500 to 900 m [33, 34]. In high altitudes, the presence of Zen oaks (*Quercus canariensis* Willd.) is recorded belonging to sub-association *Quercetosum canariensis* Br. Bl. 1953. The floristic composition accompanying this species is *Quercus suber* L., *Cytisus villosus* Pourr., *Arbutus unedo* L., *Phillyrea angustifolia* L., *Rubus ulmifolius* Schott., *Crataegus monogyna* Jacq., *Olea europea* L., *Lavendula stoechas* L., and *Smilax aspera* L. In the same region, sub-association of *Pistacietosum lentisci* [33] is recorded for the altitude below 450 m, only *Cytisus villosus* Pourr. is not present in this plant cortege.

In Nabeul at Jebel Abderrahmane and Zaghouan at Jebel Zaghouan, the vegetation is comparable to sub-*association* of *Pistacietosum lentisci.*

Rosa moschata Herrm.is distributed in Zaghouan, Nabeul, and Bizerte occupying spaces dominated by cultigen groups.

The most characteristic group of cultivated plants in Zaghouan region is composed of *Hedysarum coronarium* L., *Picris echoides* L., and *Bupleurum lancifolium* Hornem. The primitive spontaneous vegetation comprises the species of *Ceratoniasiliqua* L., *Olea europea* L., *Pistacia lentiscus* L., *Rhamnus lycoides* L. and *Phillyrea angustifolia* [30].

Many spontaneous groups of cultigen plants are determinated in Bizerte; the first one is composed by *Chrysanthemum coronarium* L. and *Galactites tomentosa* Moench. (Rafraf); the composition of the second group *Raphanus raphanistrum* L., *Mentha pulegium* L., and *Galactites tomentosa* Moench. and the third group *Hedysarum coronarium* L.*, Kremeria myconis* (L.) Maire *and Centaurea schouwii* (DC.) Holub [30].

The primitive vegetation of Nabeul region is composed by calcicole species as *Quercus coccifera* L., *Callitris articulata (Vahl.)* Murb*., Cistus libanotus L., Rosmarinus officinalis L., Globularia alypum L.* and *Erica multiflora* L. Two cultigen groupings are distinguished: In Hammamet, the grouping consists of *Raphanus* *raphanistrum* L.*, Launaearesedifolia* L. and *Artemisia campestris* L. with *Solanum sodomaeum* L. as a characteristic species which are located in the lower semi-arid bioclimatic stage with warm winters; the other grouping: *Ormenis mixta* (L.) Dumort. And *Chrysanthemum segetum* L. with *Solanum sodomaeum* L. as a characteristic species which are located in the superior semi-arid bioclimatic stage and the same climatic variant [30]. *Rosa sempervirens* L. has a wide distribution. It is found in the regions of Zaghouan, Bizerte, Sejnane, Nabeul and North-West Tunisia (Beja, Jendouba).

In Zaghouan, this species occupies the sites dominated by the Aleppo pine forest. The characteristic group consists of *Pinus halepensis* Mill. And *Rosmarinus officinalis* L., the other group is a mosaic of forest units and cultivated land composed of *Pinus halepensis* Mill. And *Rosmarinus officinalis* L. and *Scandix pecten-veneris* L.*, Hypericum crispum* L.*, Bupleurum lancifolium* Hornem. [30]. This species is localized in National Park of Zaghouan, and the grouping consists of *Pinus halepensis* Mill. And *Pistacia lentiscus* L. In the course of wadis this species is in company with *Rubus ulmifolius* Schott. and *Nerium oleander* L.

In Nabeul, the primitive forest unit is composed of the seriesof Oleo-Mastic and the groupingof *Olea europea* L. and *Brachypodium ramosum* (L.) Roem and Schult.Two cultigen groups accompany this species, the first one: *Hedysarum coronarium* L.,*Picris echoides* L. and *Galactites tomentosa* Moench. (subhumid bioclimatic stage) and the second: *Ormenis mixta* (L.) Dumort. and *Chrysanthemum segetum* L. (semi-arid bioclimatic stage) [30].

In Bizerte, *R. sempervirens*is found in two vegetative groupings:the first group is composed of *Raphanus raphanistrum* L.*, Menthapulegium* L. and *Galactites tomentosa* Moench.*,* and the second *Hedysarum coronarium* L.*, Picris echoides* L. and *Galactites tomentosa* Moench. The bioclimatic stage in these two localitiesis subhumidwith warm winters. In Sejnane, another grouping in shrubs is composed by *Olea europea* L. and *Pistacia lentiscus* L. This zone is influenced by subhumid bioclimatic with sweet winters [30].

In the North-West region (Beja and Jendouba), floristic diversity is very important attesting the adaptation of *R. sempervirens*to various environments. In fact, at Fernana and Ben Metir, the cultigen grouping is based on *Hedysarum coronarium* L.*, Picrisechoides* L. and *Galactites tomentosa* Moench. At Ain Debba and between Fernana and Ben Metir, there is the preceding grouping to which are added *Olea europea* L. and *Pistacia lentiscus* L., from Ben Metir to Ain Draham, this species is reported in the forest group of *Arbutus unedo* L.*, Erica arborea* L.*, Cistus monspeliensis* L. and *Pistacia lentiscus* L. The vegetation in theseareas belongs to the association *Quercetum suberis Pistacietosum lentisci* Br. Bl. 1953 [34]. *R. sempervirens* L. in Ain Draham, is located in Cytisus cork oak forest characterized by grouping *Quercus suber* L. and *Cytisus villosus* Pourr., giving the association *Cytiso-Quercetum suberis* Br. Bl. 1953. From Ain Draham to Babbouche, *Q. suber* is mixed with *Q. canariens* giving the grouping of *Quercus canariensis* Willd and *Agrimonia eupatoria* L. and the sub-association of *Quercetosum canariensis* Br.Bl. 1953 [34]. In Hammam Bourguiba and near Tabarka, the grouping of *Quercus suber* L.*, Pistacia lentiscus* L. and *Erica arborea* L. covers those localities. A few kilometers from Tabarka to Nefza, the vegetative grouping is similar to those reported in the Bizerte region. In Ain Sobeh and Guelta Safra (Tabarka), there is another grouping: *Quercus suber* L.*, Pistacia lentiscus* L. and *Quercus coccifera* L. In Ouechtata, this species is found in shrubs of *Olea europea* L.*, Myrtus communis* L. and *Pistacia lentiscus* L. and in vegetative grouping of *Hedysarum coronarium* L.*, Picris echoides* L.*, Hypericum crispum* L. and *Galactites tomentosa* Moench. In Nefza, the same crop group reported is comparable to that in the Bizerte region which is *Picris echoides* L.*, Mentha pulegium* L.*, Centaurea schouwii* (DC.) Holub, but the bioclimate is wet [30].

Rosa micrantha and *R. agrestis* are localized in the scrubland at the bottom of the mountain of Bargou and Kesra (Siliana) where the vegetative grouping is *Artemisia campestris, A. herba alba*, *Plantago albicans*. In Haffouz, in the mid-altitude plains, and on the small hills the grouping *Rosmarinus officinalis*, *Stipa tenassissima* and *Artemisia campestris* of the steppe come from the degradation of *Juneperus phoenicia* and at low altitude this grouping *Plantago albicans, Globularia alypum, Plantago albicans, Ilnaria aegyptiaca* replaces the forest of *Pistacia atlantica.* Those species are found in the watercourse. The bioclimates are semi-arid in Siliana (Bargou and Kesra) the bioclimates are of semi-arid (Siliana) with temperate winters and arid (Haffouz) with the same climatic variant as Siliana.

5 Phytochemistry of Tunisian *Rosa* Species

Rosa species were generally known by their medicinal and nutritional purposes according to the richness of their plant parts on bioactive secondary or primary metabolites. Rosehips of different *Rosa* species are characterized by high contents of phytonutients such as vitamin C, carotenoids (β-carotene and lycopene), tocopherols, antocyanins, polyphenolic compounds (specially flavonoids), triterpenoic acids, tannins, xanthonoids and glycerol glucosides [12, 13, 18, 19, 35, 36].

5.1 Essential Oil Composition

Rosa specieswere known by the uses of their essential oil and aromatic water as flavor and fragrance in cosmetics and additives.in food application.Essential oil composition differs according to species, plant parts, geographic origin, developmental stages, and extraction methods.In Tunisia, three different *Rosa* species were characterized for their composition on essential oils: *Rosa canina* L., *Rosa sempervirens* L. and *Rosa* × *alba.* Earlier studies have characterized essential oil composition of leaves and flowers of different *Rosa* species in Tunisia. Ghazghazi et al. [37–39] have evaluated the influence of geographic origin in flower and leaf essential oil composition of *R. canina* and *R. sempervirens.* For flowers, five Tunisian areas were investigated (Ain Drahem, Boussalem, Feija, Fernana, and Tabarka) and authorsreported the presence of twenty-six and forty-one volatile compounds in *R. sempervirens* and

R. canina profiles, respectively [39]. A clear major qualitative and quantitative chemical variability was observed between species (*R. canina* and *R. sempervirens*) and between areas of collect as regarding the individual compounds or also the chemical classes [39]. It was reported that for *R. canina* flowers, area profiles were separately dominated by β-caryophyllene or n-heneicosane or 2,4,6-trimethyl octane or other compounds,which are weakly detected (trace) in other regions (Table 1). The same thing was reported with the essential oil flowers of *R. sempervirens* [39]; some region profiles are dominated by 2-phenylethylalcohol, others includeρ-cymene as a major compound (Table 1). This variability was also observed with the dominant chemical classesand for both of the *Rosa* species [39]. Proportions differfrom one region to the other, andmonoterpene hydrocarbons dominate the majority of *R. canina* and *R. sempervirens* flower profiles (Table 1).

For the leaf essential oil characterization, Ghazghazi et al. have identified forty-nine volatile compounds in profiles of *Rosa canina* samples from two different Tunisian regions (Feija and Ain Drahem) [37] and fifty and thirty-one components for *Rosa sempervirens* samples from Tabarka and Ain Drahem, respectively [38]. As regarding *R. canina* profiles, the two leaf samples (Feija and Ain Drahem) were qualitatively correlated but a slight difference was recorded in compound proportions [37], whereas, for the essential oil composition of *R. sempervirens* leaves, a small variability was recorded between regions, in both of qualitative and quantitative data [38]. Whatever was the origin of the collection, leaf essential oils were dominated by the class of non-terpenoids and proportions were from 59.7 to 63.8% for *R. canina* and from 56.6 to 87.8% for *R. sempervirens* (Table 1). The hexadecanoic acid was reported as the major compound either for *R. canina* (15.5–23.2%) or for *R. sempervirens* (25.8–41.9%) and profiles of these two species were also dominated by vitispirane (9.1–22.5%) and phytol acetate (10.5–11.8%), respectively (Table 1) [37, 38].

Generally speaking, qualitative and quantitative differences could be related to biotic and abiotic factors, nutriments, etc.…, which influence the plant metabolite biosynthetic pathways and play accordingly a key role in the chemical variation of essential oil composition.

In other studies, Hosni et al. [40] have campared the essential oil composition of *R. canina* flowers separated according to floral parts and developmental stages. The same comparison was conducted between essential oil extraction methods [41]. Essential results were recapitulated in Table 1. Hosni et al. [40, 41] found quantitative variability between studied parameters and the major compounds of flower aromatic waters were eugenol and 2-phenethyl alcohol. The profiles most abundant groups are alcohols and alkanes (Table 1).

For *Rosa* × *alba* [42], the major compounds of essential oil composition were linalool for leaves (21.1%), eugenol and 2-phenethyl alcohol for flowers (39.4 and 12.9%, respectively) and docosane and tetracosane for fruits (27.8 and 17.7%, respectively). All *Rosa* × *alba* profiles (leaves, flowers, and fruits) were dominated by alkane/alkene and alcohol groups [42].

Table 1 Essential oil composition of different vegetal parts of *R. canina* and *R. sempervirens* from different areas of Tunisia [37–42]

Species	Plant parts	Area of collect	Extraction procedure	Major compounds (contents %)	Major classes (contents %)	References
Rosa canina L.	Flowers	Ain Draham	Hydrodistillation using a Clevenger-type apparatus	β-caryophyllene (32.0%) Geraniol (20.8%) 1,4-hydroxy-9-epi-(E)-caryophyllene (8.9%) n-heneicosane (4.7%) Citronellol (4.5%)	Oxygenated monoterpenes (32.7%) Sesquiterpene hydrocarbons (36.8%)	[39]
		Boussalem		n-heneicosane (28.9%) ρ-cymene (11.5%) β-caryophyllene (11.0%) γ-terpinene (7.8%) Geraniol (trace – 20.8%) 4,7-dimethyl undecane (6.5%)	Monoterpene hydrocarbons (32.7%) Non-terpenoids (45.1%)	
		Feija		ρ-cymene (14.4%) Limonene (11.0%) γ-terpinene (10.5%) n-pentadecane (7.8%) α-pinene 6.1%)	Monoterpene hydrocarbons (53.0%) Non-terpenoids (32.1%)	
		Fernana		2,4,6-trimethyl octane (9.1%) n-undecane (8.0%) Geraniol (7.6%) n-pentadecane (5.8%) ρ-cymene (4.9%)	Monoterpene hydrocarbons (16.2%) Non-terpenoids (40.0%)	

(continued)

Table 1 (continued)

Species	Plant parts	Area of collect	Extraction procedure	Major compounds (contents %)	Major classes (contents %)	References
		Mograne	Conventional hydrodistillation	Eugenol (45%) 2-phenethyl alcohol (13.6%) Nonadecane (6.5%) 1-heptadecene (6.0%) n-heneicosane (4.4%)	Alcohols (59.3%) Alkanes / Alkenes (25.3%)	[41]
			Dry distillation at 50 °C	2-phenethyl alcohol (58.4%) Eugenol (23.7%)	Alcohols (83.0%)	
			Dry distillation at 100 °C	Eugenol (22.9%) n-heneicosane (10.2%) Nonadecane (10.1%) 8-heptadecene (6.8%) 2-phenethyl alcohol (4.5%)	Alkanes / Alkenes (37.8%) Alcohols (27.4%)	
	Flowers with closed sepals	Mograne	Essential oil extraction by overnight maceration of plant material in hexane	Nonadecane (17.3%) 2-phenethyl alcohol (12.1%) Hexadecane (7.9%) n-heneicosane (7.8%) n-eicosane (6.3%)	Hydrocarbons (58.9%) Benzenoids (12.1%)	[40]
	Flowers with sepals attached in their basal parts			2-phenethyl alcohol (23.6%) Nonadecane (13.5%) n-eicosane (7.4%) Hexadecane (6.8%) n-heneicosane (6.4%)	Hydrocarbons (52.3%) Benzenoids (23.6%)	

(continued)

Table 1 (continued)

Species	Plant parts	Area of collect	Extraction procedure	Major compounds (contents %)	Major classes (contents %)	References
	Flowers with completely separated sepals and expanded petals			2-phenethyl alcohol (39.3%) Eugenol (7.4%) Hexadecane (7.2%) 1-heptadecene (5.9%) Tetradecane (6.1%)	Hydrocarbons (41.1%) Benzenoids (39.3%)	
	Sepals			n-eicosane (21.6%) n-heneicosane (17.2%) Nonadecane (11.9%) Tetradecane (6.7%) Docosane (5.3%)	Hydrocarbons (75%)	
	Petals			2-phenethyl alcohol (52.2%) Nonadecane (19.8%) n-eicosane (19.2%)	Benzenoids (52.2%) Hydrocarbons (40.1%)	
	Stamens			n-eicosane (36.8%) n-heneicosane (12.3%) Tetradecane (9.3%) Tricosane (6.7%) Hexadecane (5.6%)	Hydrocarbons (90.1%)	
	Gynoecium			Octacosane (70.7%) n-eicosane (20.3%)	Hydrocarbons (91.4%)	

(continued)

Table 1 (continued)

Species	Plant parts	Area of collect	Extraction procedure	Major compounds (contents %)	Major classes (contents %)	References
	Leaves	Feija	Hydrodistillation using a Clevenger-type apparatus	Hexadecanoic acid (23.2%) Vitispirane (9.1%) Linoleic acid (7.9%) Dodecanoic acid (6.4%) Tetradecanoic acid (5.1%)	Sesquiterpene hydrocarbons (11.1%) Oxygenated sesquiterpene (9.5%) Non-terpenoids (59.7%)	[37]
		Ain Drahem		Vitispirane (22.5%) Hexadecanoic acid (15.5%) Linoleic acid (13.5%) Phytol acetate (6.3%) Presilphiperfol-1-ene (3.7%)	Sesquiterpene hydrocarbons (11.6%) Oxygenated sesquiterpene (8.8%) Non-terpenoids (63.8%)	
Rosa sempervirens L.	Flowers	Ain Drahem	Hydrodistillation using a Clevenger-type apparatus	2-phenylethylalcohol 28.5%) ρ-cymene (10.9%) γ-terpinene (9.7%) n-tridecane (6.3%) n-pentadecane (5.8%)	Monoterpene hydrocarbons (32.8%) Non-terpenoids (48.7%)	[39]
		Fernana		2-phenylethylalcohol (93.3%) estragole (4.7%)	Non-terpenoids (93.3%)	

(continued)

Table 1 (continued)

Species	Plant parts	Area of collect	Extraction procedure	Major compounds (contents %)	Major classes (contents %)	References
		Tabarka		ρ-cymene (15.8%) γ-terpinene (11.6%) n-pentadecane (9.9%) 2,4,6-trimethyl octane (8.3%) Limonene (7.8%)	Monoterpene hydrocarbons (49.1%) Non-terpenoids (38.8%)	
	Leaves	Tabarka	Hydrodistillation using a Clevenger-type apparatus	Hexadecanoic acid (25.8%) Phytol acetate (11.8%) Linalool (9.1%) N-nonanal (9.1%) Spathulenol (6.5%) β-caryophyllene (6.5%)	Non-terpenoids (56.6%) Oxygenated monoterpenes (13.8%) Oxygenated sesquiterpene (13.0%) Sesquiterpene hydrocarbons (7.9%)	[38]
		Ain Draham		Hexadecanoic acid (41.9%) Linoleic acid (14.9%) Phytol acetate (10.5%) Dodecanoic acid (9.6%) Linalool (5.6%) N-nonanal (5.6%)	Non-terpenoids (87.8%) Oxygenated monoterpenes (7.4%)	

(continued)

Table 1 (continued)

Species	Plant parts	Area of collect	Extraction procedure	Major compounds (contents %)	Major classes (contents %)	References
Rosa × *alba*	Leaves	Mograne	Conventional hydrodistillation	Linalool (21.1%) Pentacosane (9.1%) Tetracosane (7.7%) Hexacosane (7.40%) Heptacosane (7.0%)	Alkanes / Alkenes (53.4%) Alcohols (28.7%)	[42]
	Flowers			Eugenol (39.4%) 2-phenethyl alcohol (12.9%) 1-heptadecene (6.5%) Nonadecane (6%) n-heneicosane (4.2%) Pentacosane (4.2%)	Alcohols (53.9%) Alkanes / Alkenes (33.7%)	
	Fruits			Docosane (27.8%) Tetracosane (19.7%) n-heneicosane (3.4%) Pentacosane (2.6%) Nonadecane (2.4%)	Alkanes / Alkenes (65.9%)	

5.2 Fatty Acid Composition

Previous studies have been conducted in Tunisia to evaluate the oil contents and fatty acid composition of *Rosa sp.* samples. Hosni et al. [43] have characterized *Rosa canina* L. organs. Ouerghemmi et al. [44] have compared between leaf samples of *Rosa moschata* Herrm. collected from different regions of Tunisia (Nabeul, Bizerte, and Zaghouan). Ben Cheikh-Affene et al. [8] have evaluated the inter-specific and inter-regional variation of oil contents and composition of *Rosa* seeds inside the section *Caninae*. Essential results were depicted in Table 2. Authors have reported inter-specific, inter-organ, and inter-regional variation of oil content and also fatty acid amounts.

For oil content, Hosni et al. [43] found that fruits are the most oleaginous organ in *R. canina* (1.6% vs. 0.6 and 1.1% in leaves and flowers, respectively). Ouerghemmi et al. [44] reported variation between regions, and the highest value was in *R. moschata* leaves from Zaghouan (3.18%). Ben Cheikh-Affene et al. [27] found an oil content in *R. canina* seeds (4.76%) more important than that reported by Hosni et al. [43]in fruits. *R. rubiginosa* produced the most oleaginous studied *Caninae* seeds when collected from Kairouan [27].

As regarding the fatty acid composition, *Rosa* studied species and organs were characterized by their richness on unsaturated fatty acids and amounts ranged from 55.86 to 91.45% (Table 2) with the highest values in seeds (78.85 – 91.45%) and the lowest levels in leaves of *R. moschata* from Zaghouan and Bizerte (55.86% and 58.36% respectively) and in flowers of *R. canina* (62.5%).

According to Hosni et al. [43], Ouerghemmi et al. [44] and Ben Cheikh-Affene et al. [8], linolenic acid was the major compound of *R. canina* leaves (56.8%) and flowers (34.4%) and *R. moschata* leaves (22.90 – 36.54%) and linoleic acid was the major compound of *R. canina* fruits (28.6%) and seeds (46.70%) and *R. rubiginosa* (46.06 – 52.84%), *R. dumetorum* (45.35%) and *R. pomifera* (52.75%) seeds. The second major fatty acids were oleic acid for all studied *Rosa* seeds and palmitic acid in leaves and flowers (Table 2).

These reports lead to note that *Rosa* species and organs could be used in the human diet as a good natural source of essential fatty acids which are notsynthesized by the human body in spite their key role in human health.

5.3 Ascorbic Acid Content

Ascorbic acid is the reduced form of vitamin C. It is a water-soluble vitamin which contributes to the prevention of scurvy and cancer and exhibits many other health benefits [45]. This vitamin was also used as a food additive to maintain the nutritional quality of strawberries or to create a favorable environment for probiotic bacteria [46].

Ben Cheikh-Affene et al. [47] have evaluated the ascorbic acid content of different species of *Rosa* belonging to the section *Caninae* (*R. pomifera* L., *R. rubiginosa* L.,

Table 2 MajorFatty acid composition (expressed as percentage of total fatty acids) of some Tunisia *Rosa sp.* parts [27, 43, 44]

Species	Plant parts	Area of collect	Oil contents (%)	Major compounds (contents %)	Major classes (contents %)	References
Rosa canina L.	Leaves	Mograne	0.6	Linolenic acid (56.8%) Palmitic acid (16.8%) Linoleic acid (15.6%)	UFA (76.5%)	[43]
	Flowers		1.1	Linolenic acid (34.4%) Palmitic acid (19.5%) Stearic acid (16.4%)	UFA (62.5%)	
	Fruits		1.6	Linoleic acid (28.6%) Linolenic acid (24.4%) Oleic acid (19.8%)	UFA (73.4%)	
	Seeds	Zaghouan	4.76	Linoleic acid (46.70%) Oleic acid (16.69%) Linolenic acid (15.27%)	UFA (79.46%)	[27]
Rosa moschata Herrm.	Leaves	Nabeul	2.48	Linolenic acid (36.54%) Palmitic acid (15.79%) Gadoleic acid (14.51%)	UFA (70.57%)	[44]
		Bizerte	2.15	Linolenic acid (29.41%) Palmitic acid (19.31%) Stearic acid (17.06%)	UFA (58.36%)	

(continued)

Table 2 (continued)

Species	Plant parts	Area of collect	Oil contents (%)	Major compounds (contents %)	Major classes (contents %)	References
		Zaghouan	3.18	Palmitic acid (26.39%) Linolenic acid (22.90%) Oleic acid (16.06%)	UFA (55.86%)	
Rosa rubiginosa L.	Seeds	Beja	5.71	Linoleic acid (46.06%) Oleic acid (16.50%) Linolenic acid (15.70%)	UFA (78.85%)	[27]
		Kairouan	10.66	Linoleic acid (52.84%) Oleic acid (18.40%) Linolenic acid (18.56%)	UFA (90.55%)	
Rosa dumetorum Thuill.	Seeds	Seliana	6.66	Linoleic acid (45.35%) Oleic acid (22.24%) Linolenic acid (19.94%)	UFA (88.57%)	[27]
Rosa pomifera L.	Seeds	Kairouan	9.11	Linoleic acid (52.75%) Oleic acid (11.28%) Linolenic acid (26.93%)	UFA (91.45%)	[27]

UFA: Unsaturated fatty acids

R. dumetorum Thuiller and *R. canina* L.) and growing in various regions of the Northern and Centre of Tunisia. Recorded levels were ranged between 372.4 and 737.8 mg per 100 g fresh weight (mg/100 g FW) (Table 3). The highest content was found in the rose hip of *R. pomifera* from Kairouan (737.8 mg/100 g FW) and the lowest content recorded in samples of *R. dumetorum* (Siliana, 372.4 mg/100 g FW). These values are more important than those found by Kapur et al. [48] either for rose hips (168.44 mg/100 g) or for other fruits known as rich on vitamin C like black currant (184.36 mg/100 g), parseley (90.53 mg/100 g) and orange (49.42 mg/100 g).

The ascorbic acid content changed according to region variation. Kazankaya et al. [49] reported that the vitamin C content in *Rosa canina* rose hips collected from different areas of Turkey varied between 301 and 1183 mg/100 g. Gunes and Sen [50] found levels between 282 and 1173 mg/100 g. Demir and Ozcan [51] have analyzed Rose hip fruits from two Turkish regions and recorded two different values (2365 and 2712 mg/100 g). Ben Cheikh-Affene et al. [47] showed significant variability in ascorbic acid contents between species and provinces in Tunisia [47]. Fascella et al. [18] have studied also the variation of vitamin C content between different Sicilian rose hips. They found that *R. canina* is the richest species (513.9 mg/100 g DW) followed by *R. sempervirens*, *R. micrantha* and *R. corymbifera* (454.3, 292.7 and 222.8 mg/100 g DW) [18]. Jiménez et al. [15] recorded variation of vitamin C content between species and accessions and the highest values was reported in *R. corymbifera* and *R. canina* rosehips (196 and 101 μg/g dry fruit). This bioactive compound was generally correlated with the greatest antioxidant ability [15].

The vitamin C content was also affected by solvent extraction and the preparation method. Nadpal et al. [12] found that puree preparations from rosehips of *R. canina* are more rich on vitamin C (3.73 mg/g DW) as compared to water and methanolic extracts for the same plant organs. For *R. sempervirens*, puree obtained from fruits includes 2.71 mg/g DW of vitamin C and this value was more important than those found in water and methanolic extracts [13].

In conclusion and whatever the species, rose hips include a high content of ascorbic acid and could be considered as a potential source of vitamin C.

5.4 Total Polyphenol and Flavonoid Contents

Several studies have described *Rosa* species and organs as important sources of natural polyphenols [28, 37, 38, 43, 47]. Essential results were recapitulated in Table 3. Ghazghazi and coworkers [37, 38] have compared the total polyphenol contents (TPC) of leaf methanolic extracts of *Rosa canina* and *Rosa sempervirens* from different localities in Northern of Tunisia (Ain Drahem, Feija, and Tabarka). TPC results of *R. canina* leaves were reported to be more important than those of *R. sempervirens*[37, 38] and values ranged from 5.42 to 9.21 mg gallic acid equivalents/ml (GAE/ml) for *R. canina* and from 1.2 to 7.5 mg GAE/ml for *R. sempervirens* (Table 3). These authors have recorded significant differences between

Table 3 Total phytochemical contents in some *Rosa* species grown in Tunisia [8, 28, 37, 38, 43, 47]

Species	Plant organs	Area of collect	Used extracts	Total contents				References
				Polyphenol	Flavonoid	Carotenoid	Ascorbic acid	
Rosa moschata Herrm.	Leaves	Nabeul	Ethyl acetate extracts after defatting step with hexane	211 µg GAE/mg DW				[28]
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	464 µg GAE/mg DW				
		Bizerte	Ethyl acetate extracts after defatting step with hexane	156 µg GAE/mg DW				
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	267 µg GAE/mg DW				
		Zaghouan	Ethyl acetate extracts after defatting step with hexane	147 µg GAE/mg DW				

(continued)

Table 3 (continued)

Species	Plant organs	Area of collect	Used extracts	Total contents				References
				Polyphenol	Flavonoid	Carotenoid	Ascorbic acid	
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	288 µg GAE/mg DW				
	Stems	Nabeul	Ethyl acetate extracts after defatting step with hexane	210 µg GAE/mg DW				[8]
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	317 µg GAE/mg DW				
		Bizerte	Ethyl acetate extracts after defatting step with hexane	128 µg GAE/mg DW				

(continued)

Table 3 (continued)

Species	Plant organs	Area of collect	Used extracts	Total contents				References
				Polyphenol	Flavonoid	Carotenoid	Ascorbic acid	
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	266 µg GAE/mg DW				
		Zaghouan	Ethyl acetate extracts after defatting step with hexane	150 µg GAE/mg DW				
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	166 µg GAE/mg DW				

(continued)

Table 3 (continued)

Species	Plant organs	Area of collect	Used extracts	Total contents				References
				Polyphenol	Flavonoid	Carotenoid	Ascorbic acid	
Rosa canina L.	Leaves	Ain Drahem	Methanolic extracts (after two defatting steps with hexane and dichloromethane using a Soxhlet apparatus)	5.42–9.21 mg GAE/ml	0.38–0.44 mg RE/ml			[37]
		Feija		7.24–8.62 mg GAE/ml	0.11–0.41 mg RE/ml			
		Feija	Ethyl acetate extracts after defatting step with hexane	197 µg GAE/mg DW				[28]
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	255 µg GAE/mg DW				
		Mograne	Methanol-HCl 6 M (20:5)	105.4 mg GAE/g DW				[43]

(continued)

Table 3 (continued)

Species	Plant organs	Area of collect	Used extracts	Total contents				References
				Polyphenol	Flavonoid	Carotenoid	Ascorbic acid	
	Stems	Feija	Ethyl acetate extracts after defatting step with hexane	208 µg GAE/mg DW				[8]
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	285 µg GAE/mg DW				
	Flowers	Mograne	Methanol-HCl 6 M (20:5)	81.2 mg GAE/g DW				[43]
	Fruits	Mograne	Methanol-HCl 6 M (20:5)	87.4 mg GAE/g DW				[43]
	Rose hips (flesh part)	Zaghouan	Methanolic extracts	34.6 mg GAE/g DW				[47]
			Acetone–water extracts (80%)			206.4 µg/g FW		
			Ascorbic acid extract				468.3 mg/100 g FW	

(continued)

Table 3 (continued)

Species	Plant organs	Area of collect	Used extracts	Total contents				References
				Polyphenol	Flavonoid	Carotenoid	Ascorbic acid	
Rosa sempervirens L.	Leaves	Tabarka	Methanolic extracts (after two defatting steps with hexane and dichloromethane using a Soxhlet apparatus)	1.2 – 1.4 mg GAE/ml	0.06 – 0.10 mg RE/ml			[38]
		Ain Draham		4.9–7.5 mg GAE/ml	0.23–0.37 mg RE/ml			
		Bizerte	Ethyl acetate extracts after defatting step with hexane	311 µg GAE/mg DW				[28]
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	291 µg GAE/mg DW				

(continued)

Table 3 (continued)

Species	Plant organs	Area of collect	Used extracts	Total contents				References
				Polyphenol	Flavonoid	Carotenoid	Ascorbic acid	
		Sajnane	Ethyl acetate extracts after defatting step with hexane	177 µg GAE/mg DW				
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	240 µg GAE/mg DW				
		Zaghouan	Ethyl acetate extracts after defatting step with hexane	197 µg GAE/mg DW				
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	243 µg GAE/mg DW				

(continued)

Table 3 (continued)

Species	Plant organs	Area of collect	Used extracts	Total contents				References
				Polyphenol	Flavonoid	Carotenoid	Ascorbic acid	
		Jendouba	Ethyl acetate extracts after defatting step with hexane	414 µg GAE/mg DW				
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	340 µg GAE/mg DW				
	Stems	Bizerte	Ethyl acetate extracts after defatting step with hexane	188 µg GAE/mg DW				
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	263 µg GAE/mg DW				[8]

(continued)

Table 3 (continued)

Species	Plant organs	Area of collect	Used extracts	Total contents				References
				Polyphenol	Flavonoid	Carotenoid	Ascorbic acid	
		Sajnane	Ethyl acetate extracts after defatting step with hexane	220 µg GAE/mg DW				
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	185 µg GAE/mg DW				
		Zaghouan	Ethyl acetate extracts after defatting step with hexane	158 µg GAE/mg DW				
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	230 µg GAE/mg DW				

(continued)

Table 3 (continued)

Species	Plant organs	Area of collect	Used extracts	Total contents				References
				Polyphenol	Flavonoid	Carotenoid	Ascorbic acid	
		Jendouba	Ethyl acetate extracts after defatting step with hexane	292 µg GAE/mg DW				
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	309 µg GAE/mg DW				
Rosa pomifera L	Rose hips (flesh part)	Kairouan	Methanolic extracts	69 mg GAE/g DW				[47]
			Acetone–water extracts (80%)			667.5 µg/g FW		
			Ascorbic acid extract				737.8 mg/100 g FW	
Rosa rubiginosa L	Rose hips (flesh part)	Kairouan	Methanolic extracts	33.0 mg GAE/g DW				[47]
			Acetone–water extracts (80%)			373.3 µg/g FW		

(continued)

Table 3 (continued)

Species	Plant organs	Area of collect	Used extracts	Total contents				References
				Polyphenol	Flavonoid	Carotenoid	Ascorbic acid	
			Ascorbic acid extract				384.0 mg/100 g FW	
		Beja	Methanolic extracts	25.2 mg GAE/g DW				[47]
			Acetone–water extracts (80%)			608.8 µg/g FW		
			Ascorbic acid extract				545.0 mg/100 g FW	
Rosa dumetorum Thuiller	Rose hips (flesh part)	Beja	Methanolic extracts	25.4 GAE/g DW				[47]
			Acetone–water extracts (80%)			590.9 µg/g FW		
			Ascorbic acid extract				433.8 mg/100 g FW	
		Siliana	Methanolic extracts	37.0 mg GAE/g DW				
			Acetone–water extracts (80%)			446.9 µg/g FW		
			Ascorbic acid extract				372.4 mg/100 g FW	

GAE = Gallic Acid Equivalent – RE = Rutin Equivalent – DW = Dry Weight – FW = Fresh Weight leaf samples from different sites and variations could be explained by the environmental influences [37, 38]. The same study was conducted by Ouerghemmi et al. [28] and Ouerghemmi [8], and comparison have concerned leaf and stem ethyl acetate (EtOAC) and methanolic (MeOH) extracts of *R. canina* from Feija, *R. moschata* from Nabeul, Bizerte and Zaghouan and *R. sempervirens* from Bizerte, Sajnane, Zaghouan, and Jendouba. Several differences were reporded according to species, organic extract, and region variation. Values ranged from 197 to 285 μg GAE/mg dry weight (DW) for *R. canina*, from 147 to 464 μg GAE/mg DW for *R. moschata* and from 177 to 414 μg GAE/mg DW for *R. sempervirens* [28]. The highest TPC content was found in leaves of *R. sempervirens* from Jendouba (414 μg GAE/mg DW) and *R. moschata* from Nabeul (464 μg GAE/mg DW) for EtOAC and MeOH extracts, respectively. *R. canina* leaves were moderately rich on total polyphenols as characterized by Ouerghemmi et al. [28], but values were more important than those found by Hosni et al. [43] either with EtOAC or with MeOH extracts (197 and 255 μg GAE/mg DW, respectively). In Hosni et al. [43], TPC amounts of *R. canina* from Mograne were about 81.2, 87.4, and 105.7 mg GAE/g DW in flowers, fruits, and leaves, respectively. Differences could be attributed to the uses of different extraction solvents and conditions. This hypothesis was supported by Nadpal et al. [12, 13]. They found that prepared puree from *R. canina* and *R. sempervirens* rosehips showed the greatest values of total polyphenol (96.2 and 82.8 mg GAE/g DW, respectively) and flavonoid contents (2.94 and 4.99 mg QE/g DW, respectively) compared to jam, methanolic and water extracts [12, 13].

The total polyphenol content was also investigated for rose hips. Ben Cheikh-Affene et al. [47] found important levels of TPC in fruits of four species of *Rosa* belonging to the section *Caninae* and growing in different areas of Tunisia; *R. pomifera* (Kairouan), *R. rubiginosa* (Kairoun and Beja), *R. dumetorum* (Siliana and Beja) and *R. canina* (Zaghouan). The highest value was recorded in *R. pomifera* rose hips and the lowest in samples from Beja (25.2 and 25.4 mgGAE/g fresh weight (FW) for *R. rubiginosa* and *R. dumetorum*, respectively) [47].

On the other hand, *Rosa* species are classified as flavonoid rich plants. Ghazghazi et al. [37, 38] showed that the total flavonoid content (TFC) of methanolic extracts of *R. canina* and *R. sempervirens* leaves varied from one region to another in Northern of Tunisia. Amounts were ranged between 0.11 and 0.44 mg rutin equivalent / ml extract (mg RE/ml) for *R. canina* and from 0.06 to 0.37 mg RE/ml for *R. sempervirens* (Table 3). The mean value was more important in *R. canina* leaves as compared to *R. sempervirens* ones (0.34 and 0.19 mg RE/ml, respectively) [37, 38].

5.5 *Polyphenol Composition*

Polyphenols or phenolic compounds represent an extremely diverse chemical subclass of secondary metabolites. They are widely distributed in the plant kingdom and form an integral part of the human diet. These compounds are known as bioactive substances and exhibit several biological effects such as anti-inflammatory, antioxidant, cardioprotective, vasodilatory, anticarcinogenic, anti-thrombotic activities… [12, 36].

Some studies have characterized the polyphenol composition of Tunisian *Rosa* species, and findings were depicted in Table 4.

Hosni et al. [43] have investigated the polyphenol composition of *R. canina* leaves, flowers, and fruits, but Ouerghemmi et al. [28, 52] have compared the leaf [28] and stem [52] composition of three species (*R. canina*, *R. moschata,* and *R. sempervirens*) collected from different Tunisian areas (Feija, Nabeul, Bizerte, Zaghouan, Sajnane and Jendouba). These reports [28, 43, 52] have used two different procedures of extraction and showed segregate results.When leaves, flowers, and fruits of *R. canina* were extracted by methanol-HCl 6 M (20:5), eleven compounds were identified belonging to four sub-classes: phenolic acids (gallic, cafeic, ellagic and ferulic acids), flavanols (catechin, epicatechin gallate and epicatechin), flavonols (quercetin, kaempferol and quercitrin) and phenolic alcohols (tyrosol) [43]. Ellagic acid and quercetin are detected as the major compounds in the three profiles and reported amounts are 5611.5 and 4196.3 μg/g in leaves, 6378.4 and 5832.7 μg/g in flowers and 8469.6 and 4648.3 μg/g in fruits, respectively [43]. Phenolic acids, cathechin, epicathechin, and kaempferol are abundant in fruits, quercetin is higher in flowers, and epicatechin gallate is more important in leaves [43]. Six years later, Ouerghemmi et al. [28] have performed the polyphenol composition of *R. canina*, *R. moschata,* and *R. sempervirens* extracts obtained by maceration of the leaf powder in increasing order of solvent polarity (hexane, ethyl acetate and methanol). Chromatographic results reported the presence of fifteen major compounds: three flavanols (catechin, epicatechin and epicatechin gallate), eleven flavonols (kaempferol and quercetin derivatives) and one flavanone (aromadendrine derivative). The same results were found with stem extracts [52]. In opposition to Hosni et al. [43], Ouerghemmi et al. [28, 52] reported that phenolic acids were detected in very small amounts in all tested *Rosa* extracts. Whatever was the region of collect or the used extract, major compounds are quercetin 3-O-glucoside for *R. canina* (6700–22,700 μg/g DW), quercitrin for *R. moschata* (21,300–68,400 μg/g DW) and aromadendrin O-hexoside-deoxyhexoside (35,300–93,300 μg/g DW) for *R. sempervirens* [28]. *R. canina* profiles were characterized by the diversity of kaempferol derivatives in opposition to *R. moschata* and *R. sempervirens* profiles, which included a higher number of quercetin derivatives. The chemical composition of *Synstylae* species (*R. moschata* and *R. sempervirens*) was qualitatively related, leading to the use of polyphenols as chemotaxonomic markers [28]. Quantitative differences were recorded between solvent extracts (ethyl acetate and methanol), between organs (leaves and stems) and also between regions of collect (Nabeul, Bizerte, Zaghouan, Sajnane, and Jendouba) [28, 52]. In another recent work, Nadpal et al. [12] have compared between different rosehip preparations of *R. canina.* They reported the presence as major compounds of quercitrin in water and methanolic extracts and gallic acid and epicatechin in puree and jam preparations respectively [12]. Two years later, these authors have compared in 2018, the polyphenol profiles of different extracts obtained from *R. sempervirens* fruits. Catechin was the major compound of jam, puree and water and methanol extracts of fresh rosehips (94, 203, 118 and 189 μg/g DW, respectively). But aqueous and methanolic extracts of air dried rosehips were dominated by gallic acid (185 μg/g DW) and protocatechic acid (243 μg/g DW), respectively [13].

In conclusion, *Rosa* species and its parts could serve as a natural source of polyphenols. Composition and synthesis of these metabolites are dependent on environmental conditions, plant species and tissus, genetic and ontogenic factors and also on solvent extraction system.

5.6 Carotenoid Content and Composition

The carotenoids derived from the Latin *Daucus carota* and evoke natural, fatty-soluble, orange or yellow pigments, which are found in plants, fruits, vegetables as well as in animals or humans.They serve, in nature, to color the feathering of certain birds like flamingos or to protect the plant chlorophyll against oxidation and participate in photosynthesis. Rose plants are rich in carotenoids, especially the pericarp of their fruits. Ben Cheikh-Affene et al. [47] have noted the high content of carotenoids in rose hips when compared to carrot, papaya, guava, and tomato. As reported in Table 3, carotenoid contents ranged from 206.4 to 667.5 μg/g FW and varied between species (*R. pomifera* L., *R. rubiginosa* L., *R. dumetorum* Thuiller and *R. canina* L.) and regions (Kairouan, Beja, Siliana, and Zaghouan). The highest content was recorded in *R. pomifera* fruits, and value was three times greater than that found in *R. canina* rose hips [47].

As regarding the carotenoid composition, Ghazghazi et al. [37, 38] have analyzed the pericarps of two *Rosa* species (*R. canina* and *R. sempervirens*) from different Northern regions of Tunisia (Feija, Ain Drahem, and Tabarka). *R. canina* pericarps showed high values of β-carotene (217 and 268 μg/ml) and lycopene (31 and 50 μg/ml)in samples collected from Feija and Ain Drahem, respectively [37]. The β-carotene contents of *R. sempervirens* pericarps collected from Ain Drahem and Tabarka were significantly inferior to those recorded for *R. canina* and measured about 100 and 180 μg/ml, respectively [38]. Authors explained the recorded quantitative variability of carotenoid pigments as a result of solar radiation and climatic influences [37, 38]. The carotenoid biosynthesis could act as a plant defense mechanism against high solar radiation and prevent the photosynthetic system damage [38].

6 Biological Activity

As general speaking, plants are biologically effective according to the presence of bioactive compounds in their extracts [12, 13, 21, 23, 36]. *Rosa* extracts are a source of bioactive phytochemicals and show antioxidant, analgesic, antibacterial, antifungal, cytotoxic, anti-inflammatory, anti-arthritic, antiproliferative and many other several

Table 4 Polyphenol composition of some *Rosa* species grown in different areas of Tunisia [28, 43, 52]

Rosa species	Plant part	Area of collect	Analyzed extract	Polyphenols	Content (µg/g DW)	References
Rosa moschata Herrm.	Leaves	Nabeul	Ethyl acetate _ Methanol extracts	Catechin	Trace _ 5900	[28]
				Quercetin di-O-hexoside	100 _ 3300	
				Epicatechin gallate	Trace _ 2100	
				Epicatechin	100 _ 800	
				Rutin	1600 _ 2400	
				Quercetin 3-O-glucoside	4900 _ 17,000	
				Kaempferol O-hexoside-deoxyhexoside	2800 _ 6200	
				Aromadendrin O-hexoside-deoxyhexoside	52,300 _ 15,600	
				Kaempferol 3-O-rutinoside	1100 _ 1900	
				Quercetin O-pentoside 1	800 _ 800	
				Quercetin O-pentoside 2	350 _ 1300	
				Quercitrin	68,400 _ 50,500	
				Kaempferol O-rhamnoside	8200 _ 1800	
		Bizerte	Ethyl acetate _ Methanol extracts	Catechin	100 _ 8200	[28]
				Quercetin di-O-hexoside	Trace _ 1900	
				Epicatechin gallate	Trace _ 900	
				Epicatechin	Trace _ 1000	
				Rutin	500 _ 2400	
				Quercetin 3-O-glucoside	700 _ 5200	

(continued)

Table 4 (continued)

Rosa species	Plant part	Area of collect	Analyzed extract	Polyphenols	Content (µg/g DW)	References
				Kaempferol O-hexoside-deoxyhexoside	100 _ 1100	
				Aromadendrin O-hexoside-deoxyhexoside	24,400 _ 22,500	
				Kaempferol 3-O-rutinoside	Trace _ 900	
				Quercetin O-pentoside 1	300 _ 900	
				Quercetin O-pentoside 2	1000 _ 1300	
				Quercitrin	40,700 _ 50,100	
				Kaempferol O-rhamnoside	4200 _ 2700	
		Zaghouan	Ethyl acetate _ Methanol extracts	Catechin	Trace _ 4000	[28]
				Quercetin di-O-hexoside	Trace _ 500	
				Epicatechin gallate	Trace _ 300	
				Epicatechin	Trace _ 500	
				Rutin	100 _ 1300	
				Quercetin 3-O-glucoside	1500 _ 6600	
				Kaempferol O-hexoside-deoxyhexoside	Trace _ trace	
				Aromadendrin O-hexoside-deoxyhexoside	4800 _ 1200	
				Kaempferol 3-O-rutinoside	100 _ 900	
				Quercetin O-pentoside 1	300 _ 1400	
				Quercetin O-pentoside 2	100 _ 200	

(continued)

Table 4 (continued)

Rosa species	Plant part	Area of collect	Analyzed extract	Polyphenols	Content (µg/g DW)	References
				Quercitrin	21,300 _ 43,300	
				Kaempferol O-rhamnoside	1800 _ 2200	
	Stems	Nabeul	Ethyl acetate _ Methanol extracts	Catechin	300 _ 2200	[52]
				Quercetin di-O-hexoside	Trace _ 500	
				Epicatechin gallate	Trace _ 400	
				Epicatechin	Trace _ 200	
				Rutin	500 _ 1300	
				Quercetin 3-O-glucoside	2300 _ 5500	
				Kaempferol O-hexoside-deoxyhexoside	9400 _ 6200	
				Aromadendrin O-hexoside-deoxyhexoside	12,100 _ 5600	
				Kaempferol 3-O-rutinoside	Trace _ 300	
				Quercetin O-pentoside 1	1000 _ 600	
				Quercetin O-pentoside 2	1700 _ 900	
				Quercitrin	33,500 _ 13,200	
				Kaempferol O-rhamnoside	1700 _ 500	
		Bizerte	Ethyl acetate _ Methanol extracts	Catechin	300_ 4800	[52]
				Quercetin di-O-hexoside	Trace _ 600	
				Epicatechin gallate	Trace _ 100	
				Epicatechin	Trace _ 100	

(continued)

Table 4 (continued)

Rosa species	Plant part	Area of collect	Analyzed extract	Polyphenols	Content (µg/g DW)	References
				Rutin	300 _ 1100	
				Quercetin 3-O-glucoside	900 _ 1500	
				Kaempferol O-hexoside-deoxyhexoside	2400 _ 2200	
				Aromadendrin O-hexoside-deoxyhexoside	6500 _ 4200	
				Kaempferol 3-O-rutinoside	100 _ 300	
				Quercetin O-pentoside 1	700 _ 700	
				Quercetin O-pentoside 2	800 _ 700	
				Quercitrin	17,300 _ 10,000	
				Kaempferol O-rhamnoside	600 _ 200	
		Zaghouan	Ethyl acetate _ Methanol extracts	Catechin	300 _ 2500	[52]
				Quercetin di-O-hexoside	Trace _ 400	
				Epicatechin gallate	Trace _ 200	
				Epicatechin	Trace _ 100	
				Rutin	100 _ 1300	
				Quercetin 3-O-glucoside	800 _ 4600	
				Kaempferol O-hexoside-deoxyhexoside	2100 _ 5000	
				Aromadendrin O-hexoside-deoxyhexoside	5000 _ 2600	
				Kaempferol 3-O-rutinoside	Trace _ 100	

(continued)

Table 4 (continued)

Rosa species	Plant part	Area of collect	Analyzed extract	Polyphenols	Content (µg/g DW)	References
				Quercetin O-pentoside 1	400_ 600	
				Quercetin O-pentoside 2	500 _ 500	
				Quercitrin	10,700 _ 9500	
				Kaempferol O-rhamnoside	1000 _ 500	
Rosa canina L.	Leaves	Mograne	Methanol-HCl 6 M (20:5)	Gallic acid	707.6	[43]
				Cafeic acid	6.4	
				Tyrosol	1.6	
				Catechin	576.5	
				Epicatechin	33.9	
				Epicatechin gallate	756.0	
				Ellagic acid	5611.5	
				Quercitrin	1.3	
				Ferulic acid	52.8	
				Quercetin	4196.3	
				Kaempherol	22.4	
		Feija, Jendouba	Ethyl acetate _ Methanol extracts	Catechin	700 _ 3300	[28]
				Quercetin di-O-hexoside	Trace _ 1700	
				Epicatechin gallate	1700 _ 4600	
				Epicatechin	Trace _ 2500	
				Rutin	200 _ 1500	
				Quercetin 3-O-glucoside	6700 _ 22,700	

(continued)

Table 4 (continued)

Rosa species	Plant part	Area of collect	Analyzed extract	Polyphenols	Content (µg/g DW)	References
				Kaempferol O-hexoside-deoxyhexoside	6000 _ 8300	
				Kaempferol 3-O-rutinoside	300 _ 1100	
				Kaempferol 7-O-glucoside	200 _ 1200	
				Kaempferol 3-O-glucoside	1400 _ 2800	
				Quercitrin	Trace _ 1000	
	Stems	Feija, Jendouba	Ethyl acetate _ Methanol extracts	Catechin	2200 _ 1700	[52]
				Quercetin di-O-hexoside	Trace _ 200	
				Epicatechin gallate	Trace _ 300	
				Epicatechin	Trace _ 800	
				Rutin	200 _ 1500	
				Quercetin 3-O-glucoside	3700 _ 6900	
				Kaempferol O-hexoside-deoxyhexoside	5500 _ 4300	
				Kaempferol 3-O-rutinoside	100 _ 100	
				Kaempferol 7-O-glucoside	100 _ 200	
				Kaempferol 3-O-glucoside	400 _ 200	
				Quercitrin	300 _ 1000	
	Flowers	Mograne	Methanol-HCl 6 M (20:5)	Gallic acid	519.2	[43]
				Cafeic acid	8.23	
				Tyrosol	0.9	

(continued)

Table 4 (continued)

Rosa species	Plant part	Area of collect	Analyzed extract	Polyphenols	Content (µg/g DW)	References
				Catechin	463.7	
				Epicatechin	23.7	
				Epicatechin gallate	641.6	
				Ellagic acid	6378.4	
				Quercitrin	0.5	
				Ferulic acid	37.4	
				Quercetin	5832.7	
				Kaempherol	61.3	
	Fruits	Mograne	Methanol-HCl 6 M (20:5)	Gallic acid	734.4	[43]
				Cafeic acid	13.8	
				Tyrosol	0.4	
				Catechin	872	
				Epicatechin	83.3	
				Epicatechin gallate	725.7	
				Ellagic acid	8469.6	
				Quercitrin	0.7	
				Ferulic acid	91.2	
				Quercetin	4648.3	
				Kaempherol	77.8	
Rosa sempervirens L.	Leaves	Bizerte	Ethyl acetate _ Methanol extracts	Catechin	500 _ 1600	[28]
				Quercetin di-O-hexoside	Trace _ 5200	

(continued)

Table 4 (continued)

Rosa species	Plant part	Area of collect	Analyzed extract	Polyphenols	Content (µg/g DW)	References
				Epicatechin gallate	Trace _ 2300	
				Epicatechin	Trace _ 200	
				Rutin	300 _ 1700	
				Quercetin 3-O-glucoside	400 _ 1000	
				Kaempferol O-hexoside-deoxyhexoside	800 _ 2200	
				Aromadendrin O-hexoside-deoxyhexoside	68,700 _ 40,000	
				Kaempferol 3-O-rutinoside	Trace _ 200	
				Quercetin O-pentoside 1	600 _ 600	
				Quercetin O-pentoside 2	2900 _ 1900	
				Quercitrin	58,500 _ 26,800	
				Kaempferol O-rhamnoside	1800 _ 1600	
		Sajnane	Ethyl acetate _ Methanol extracts	Catechin	900 _ 4300	[28]
				Quercetin di-O-hexoside	Trace _ 1300	
				Epicatechin gallate	Trace _ 1300	
				Epicatechin	Trace _ 300	
				Rutin	300 _ 4400	
				Quercetin 3-O-glucoside	200 _ 4200	
				Kaempferol O-hexoside-deoxyhexoside	800 _ 4100	

(continued)

Table 4 (continued)

Rosa species	Plant part	Area of collect	Analyzed extract	Polyphenols	Content (µg/g DW)	References
				Aromadendrin O-hexoside-deoxyhexoside	52,700 _ 51,600	
				Kaempferol 3-O-rutinoside	Trace _ trace	
				Quercetin O-pentoside 1	500 _ 1000	
				Quercetin O-pentoside 2	900 _ 1200	
				Quercitrin	38,300 _ 37,700	
				Kaempferol O-rhamnoside	3400 _ 2100	
		Zaghouan	Ethyl acetate _ Methanol extracts	Catechin	700 _ 1600	[28]
				Quercetin di-O-hexoside	Trace _ 2100	
				Epicatechin gallate	Trace _ 1300	
				Epicatechin	Trace _ 200	
				Rutin	300 _ 4600	
				Quercetin 3-O-glucoside	100 _ 4400	
				Kaempferol O-hexoside-deoxyhexoside	500 _ 3300	
				Aromadendrin O-hexoside-deoxyhexoside	35,300 _ 37,000	
				Kaempferol 3-O-rutinoside	Trace _ 100	
				Quercetin O-pentoside 1	300 _ 600	
				Quercetin O-pentoside 2	1800 _ 1900	
				Quercitrin	28,300 _ 23,600	

(continued)

Table 4 (continued)

Rosa species	Plant part	Area of collect	Analyzed extract	Polyphenols	Content (μg/g DW)	References
				Kaempferol O-rhamnoside	2200 _ 1300	
		Jendouba	Ethyl acetate _ Methanol extracts	Catechin	7100 _ 5300	[28]
				Quercetin di-O-hexoside	Trace _ 2100	
				Epicatechin gallate	Trace _ 2400	
				Epicatechin	Trace _ 100	
				Rutin	400 _ 3800	
				Quercetin 3-O-glucoside	500 _ 5900	
				Kaempferol O-hexoside-deoxyhexoside	500 _ 4100	
				Aromadendrin O-hexoside-deoxyhexoside	93,300 _ 59,000	
				Kaempferol 3-O-rutinoside	Trace _ 100	
				Quercetin O-pentoside 1	500 _ 600	
				Quercetin O-pentoside 2	4100 _ 2700	
				Quercitrin	51,200 _ 30,400	
				Kaempferol O-rhamnoside	4600 _ 1800	
	Stems	Bizerte	Ethyl acetate _ Methanol extracts	Catechin	5600 _ 3800	[52]
				Quercetin di-O-hexoside	Trace _ 500	
				Epicatechin gallate	Trace _ 400	
				Epicatechin	Trace _ 100	
				Rutin	1000 _ 800	

(continued)

Table 4 (continued)

Rosa species	Plant part	Area of collect	Analyzed extract	Polyphenols	Content (µg/g DW)	References
				Quercetin 3-O-glucoside	300 _ 1900	
				Kaempferol O-hexoside-deoxyhexoside	2400 _ 3500	
				Aromadendrin O-hexoside-deoxyhexoside	16,100 _ 7100	
				Kaempferol 3-O-rutinoside	Trace _ Trace	
				Quercetin O-pentoside 1	900 _ 500	
				Quercetin O-pentoside 2	4800 _ 1700	
				Quercitrin	12,100 _ 4900	
				Kaempferol O-rhamnoside	300 _ 100	
		Sajnane	Ethyl acetate _ Methanol extracts	Catechin	2900 _ 800	[52]
				Quercetin di-O-hexoside	Trace _ 500	
				Epicatechin gallate	Trace _ 200	
				Epicatechin	Trace _ 100	
				Rutin	500 _ 1500	
				Quercetin 3-O-glucoside	600 _ 2300	
				Kaempferol O-hexoside-deoxyhexoside	1700 _ 1300	
				Aromadendrin O-hexoside-deoxyhexoside	5500 _ 5400	
				Kaempferol 3-O-rutinoside	Trace _ 100	
				Quercetin O-pentoside 1	300 _ 500	

(continued)

Table 4 (continued)

Rosa species	Plant part	Area of collect	Analyzed extract	Polyphenols	Content (µg/g DW)	References
				Quercetin O-pentoside 2	500 _ 700	
				Quercitrin	6900 _ 6200	
				Kaempferol O-rhamnoside	400 _ 300	
		Zaghouan	Ethyl acetate _ Methanol extracts	Catechin	1200 _ 2500	[52]
				Quercetin di-O-hexoside	Trace _ 400	
				Epicatechin gallate	Trace _ 200	
				Epicatechin	Trace _ 100	
				Rutin	200 _ 1600	
				Quercetin 3-O-glucoside	900 _ 2100	
				Kaempferol O-hexoside-deoxyhexoside	1200 _ 1000	
				Aromadendrin O-hexoside-deoxyhexoside	3400 _ 3900	
				Kaempferol 3-O-rutinoside	Trace _ Trace	
				Quercetin O-pentoside 1	200 _ 400	
				Quercetin O-pentoside 2	1600_ 1400	
				Quercitrin	3000 _ 3300	
				Kaempferol O-rhamnoside	100_ 100	
		Jendouba	Ethyl acetate _ Methanol extracts	Catechin	3000 _ 4800	[52]
				Quercetin di-O-hexoside	Trace _ 400	
				Epicatechin gallate	Trace _ 200	

(continued)

Table 4 (continued)

Rosa species	Plant part	Area of collect	Analyzed extract	Polyphenols	Content (µg/g DW)	References
				Epicatechin	Trace _ Trace	
				Rutin	400 _ 1900	
				Quercetin 3-O-glucoside	1300 _ 1900	
				Kaempferol O-hexoside-deoxyhexoside	2500 _ 4400	
				Aromadendrin O-hexoside-deoxyhexoside	7400 _ 8500	
				Kaempferol 3-O-rutinoside	Trace _ Trace	
				Quercetin O-pentoside 1	500 _ 500	
				Quercetin O-pentoside 2	2800 _ 1600	
				Quercitrin	6700 _ 4300	
				Kaempferol O-rhamnoside	400 _ 200	

activities [12–14, 16, 18, 21, 23, 36]. Rosehips are also used as antidiabetic agent [53]. In Tunisia, roses are studied for their antioxidant and insecticidal activities.

6.1 Antioxidant Activity

The antioxidant activity of *Rosa* species in Tunisia has been well documented in several studies (Table 5). Ouerghemmi et al. [28, 52] have evaluated the antioxidant activity of leaf [28] and stem [52] extracts of *R. canina,* and two *Synstylae* species (*R. moschata* and *R. sempervirens*) collected from different regions of Tunisia, using four free radical scavenging tests; DPPH (1,1-diphenyl-2-picrylhydrazyl), the ferric reducing antioxidant power (FRAP), the Trolox equivalent antioxidant capacity (TEAC) and the oxygen radical absorbance capacity (ORAC) assays. High antioxidant power was recorded in all tested assays, and differences were found between organic extracts (ethyl acetate and methanol), *Rosa* species, and area of collect. Values ranged from 0.2 to 2.8 mmol TE g^{-1} DW for DPPH test, from 0.4 to 3.1 mmol TE g^{-1} DW for TEAC assay, from 0.7 to 4.9 mmol Fe^{2+} E g^{-1} DW for FRAP test and finally from 2.3 to 17.1 mmol TE g^{-1} DW for ORAC index [28]. Methanolic extracts showed the highest activity as compared to ethyl acetate ones except for ORAC results of *R. canina* and *R. moschata* from Nabeul [28]. *Synstylae* samples exhibited the strongest power for all used assays, but the inter-regional comparison recorded the lowest values with samples from Zaghouan [28, 52]. As general speaking, plant extracts included antioxidant compounds which could be influenced by geographic variation, growing conditions, biotic and abiotic factors… These antioxidant agents may belong to the polyphenol family. According to Ouerghemmi et al. [28], a strong correlation between polyphenol contents and antioxidant activity was recorded with *Rosa* ethyl acetate extracts as tested by means of DPPH, TEAC and FRAP assays but no correlation was found with methanolic extracts. This means to note that *Rosa* extracts are rich on polyphenols and also on other bioactive compounds influenced by the extraction system and able to exhibit several antioxidant abilities.

In the same context, Ghazghazi et al. [37, 38] have compared between regions and species to study the antioxidant activity of *Rosa* extracts. It was reported that methanolic extracts of *R. canina* and *R. sempervirens* leaves from different sites showed antioxidant activity clearly influenced by the region variation and non-correlated to phenol and flavonoid amounts [37, 38]. These samples exhibited significant inhibition in DPPH and ABTS radical formations and IC50 values ranged from 2.3 to 22.6 µg/ml for DPPH test and from 1.1 to 12.5 µg/ml for ABTS assay (Table 5). Samples of *R. sempervirens* from Tabarka localities showed the highest antioxidant power (2.3–3.5 µg/ml and 1.1–1.7 µg/ml for DPPH and ABTS respectively) as compared to those from Ain Drahem for the same species (*R. sempervirens*) or also when compared to *R. canina* leaf extracts (9.5–22.6 µg/ml for DPPH and 4.2–12.5 µg/ml for ABTS assay) [37, 38]. Generally speaking and whatever was the origin of collect, methanolic extracts of *R. sempervirens* leaves were more potent than *R. canina* to inhibit DPPH (9.59 and 15.21 µg/ml respectively) and ABTS

Table 5 Antioxidant activity of some *Rosa* species collected from different regions of Tunisia [28, 37, 38, 52]

Rosa species	Plant organs	Area of collect	Used extracts	DPPH[a,b]	ABTS (TEAC)[a,b,c,d]	FRAP[e]	ORAC[a]	References
Rosa canina L.	Leaves	Feija	Ethyl acetate extracts after defatting step with hexane	0.5[a]	0.9[a]	0.9	7.8	[28]
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	2.4[a]	2.6[a]	4.1	5.6	
			Methanolic extracts (after two defatting steps with hexane and dichloromethane using a Soxhlet apparatus)	14.1–22.6[b]	8.3–12.5[b]			[37]
			Essential oils	–	159[b]			
		Ain Drahem	Methanolic extracts (after two defatting steps with hexane and dichloromethane using a Soxhlet apparatus)	12.5–14.8[b]	6.11–10.5 [b]			
			Essential oils	–	201.8[b]			
	Pericarps	Feija	Carotenoid extracts	–	28.42[c]			
		Ain Drahem		–	46.82[c]			
	Stems	Feija	Ethyl acetate extracts after defatting step with hexane	0.5[a]	1.0[a]	1.3	17.1	[52]

(continued)

Table 5 (continued)

Rosa species	Plant organs	Area of collect	Used extracts	DPPH^{a,b}	ABTS (TEAC)^{a,b,c,d}	FRAP^{e}	ORAC^{a}	References
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	2.8^{a}	2.8^{a}	4.3	9.9	
Rosa sempervirens L.	Leaves	Tabarka	Methanolic extracts (after two defatting steps with hexane and dichloromethane using a Soxhlet apparatus)	2.3–3.5^{b}	1.1–1.7^{b}			[38]
			Essential oils	–	12.0%			
		Ain Draham	Methanolic extracts (after two defatting steps with hexane and dichloromethane using a Soxhlet apparatus)	9.5–19.6^{b}	4.2–10.0^{b}			
			Essential oils	-	7.0%			
		Bizerte	Ethyl acetate extracts after defatting step with hexane	1.4^{a}	1.7^{a}	2.9	5.7	[28]
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	2.3^{a}	2.6^{a}	3.7	6.1	
		Sajnane	Ethyl acetate extracts after defatting step with hexane	0.5^{a}	0.9^{a}	1.5	3.8	

(continued)

Table 5 (continued)

Rosa species	Plant organs	Area of collect	Used extracts	DPPH[a,b]	ABTS (TEAC)[a,b,c,d]	FRAP[e]	ORAC[a]	References
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	2.1[a]	2.5[a]	3.2	7.7	
		Zaghouan	Ethyl acetate extracts after defatting step with hexane	0.5[a]	0.8[a]	1.3	3.2	
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	2.0[a]	2.4[a]	3.4	9.1	
		Jendouba	Ethyl acetate extracts after defatting step with hexane	1.1[a]	1.6[a]	2.5	6.6	
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	2.4[a]	2.8[a]	3.9	8.3	
	Pericarps	Tabarka	Carotenoid extracts	–	59.0[d]			[38]
		Ain Draham		–	63.0[d]			
	Stems	Bizerte	Ethyl acetate extracts after defatting step with hexane	1.0[a]	1.6[a]	2.1	4.0	[52]
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	2.3[a]	2.1[a]	2.8	5.6	

(continued)

Table 5 (continued)

Rosa species	Plant organs	Area of collect	Used extracts	DPPH[a,b]	ABTS (TEAC)[a,b,c,d]	FRAP[e]	ORAC[a]	References
		Sajnane	Ethyl acetate extracts after defatting step with hexane	0.5[a]	1.1[a]	1.6	3.7	
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	1.3[a]	2.2[a]	3.2	5.3	
		Zaghouan	Ethyl acetate extracts after defatting step with hexane	0.3[a]	0.7[a]	1.2	2.3	
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	2.0[a]	2.6[a]	3.6	6.6	
		Jendouba	Ethyl acetate extracts after defatting step with hexane	0.6[a]	1.4[a]	2.0	3.9	
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	2.3[a]	2.8[a]	4.1	10.7	
Rosa moschata Herrm.	Leaves	Nabeul	Ethyl acetate extracts after defatting step with hexane	1.2[a]	1.8[a]	3.6	16.7	[28]
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	2.1[a]	1.9[a]	3.8	7.8	
		Bizerte	Ethyl acetate extracts after defatting step with hexane	0.3[a]	0.5[a]	1.0	6.5	

(continued)

Table 5 (continued)

Rosa species	Plant organs	Area of collect	Used extracts	DPPH[a,b]	ABTS (TEAC)[a,b,c,d]	FRAP[e]	ORAC[a]	References
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	2.5[a]	3.0[a]	4.0	6.8	
		Zaghouan	Ethyl acetate extracts after defatting step with hexane	0.2[a]	0.4[a]	0.8	3.6	
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	1.8[a]	2.1[a]	2.4	5.5	
	Stems	Nabeul	Ethyl acetate extracts after defatting step with hexane	0.6[a]	1.0[a]	1.7	8.3	[52]
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	2.3[a]	3.0[a]	4.7	7.7	
		Bizerte	Ethyl acetate extracts after defatting step with hexane	0.2[a]	0.4[a]	0.7	4.6	
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	2.3[a]	3.1[a]	4.9	7.5	
		Zaghouan	Ethyl acetate extracts after defatting step with hexane	0.4[a]	0.6[a]	0.9	4.8	

(continued)

Table 5 (continued)

Rosa species	Plant organs	Area of collect	Used extracts	DPPH[a,b]	ABTS (TEAC)[a,b,c,d]	FRAP[e]	ORAC[a]	References
			Methanolic extracts after defatting step with hexane and extraction with ethyl acetate	1.9[a]	2.2[a]	2.6	5.0	

DPPH = 2.2'-Diphenyl-1-picrylhydrazyl radical; ABTS = 2.2'-azino-bis-3-ethylbenzothiazoline-6-sulfonic acid); FRAP = Ferric Reducing/Antioxidant Power; ORAC = Oxygen Radical Antioxidant Capacity

[a] Results were expressed as mmol of Trolox equivalents/g of dry weight (mmol TE g^{-1} DW)

[b] Data were reported as the sample concentration providing 50% inhibition of DPPH or ABTS radical formation (IC50) and expressed as μg/ml

[c] Results were expressed as percentage of radical inhibition (%) obtained by 25 μl of pure extract

[d] Results were expressed as percentage of radical inhibition (%) obtained by 10 μl of pure extract

[e] FRAP results were expressed asmmol of Fe^{2+} equivalents/g of dry weight (mmol Fe^{2+} E g^{-1} DW)

radical formation (4.76 and 9.91 μg/ml respectively) in spite they included the lowest contents of polyphenol and flavonoids [37, 38].

Another leaf extract of *R. canina* (essential oils) was demonstrated to possess antioxidant ability by scavenging ABTS cation radical [37] but IC50 values were lower than those recorded by methanolic extracts (Table 5). According to Ghazghazi et al. [38], leaf essential oil of *R. sempervirens* showed very low ability to scavenge ABTS radicals and percentages did not exceed 15% (Table 5).

Ghazghazi et al. [37] have also reported a positive correlation between β-carotene and lycopene amounts and the antioxidant activity of carotenoid extracts from *R. canina* pericarps. This was explained by the potent property of carotenoids as quenchers of reactive oxygen species [37]. In contrast, carotenoid extracts of *R. sempervirens* pericarps were more active against ABTS radical formation (59.0–63.0%, Table 5) as compared to those of *R. canina* but no correlation was reported with β-carotene levels [38].

6.2 *Insecticidal Activity*

Rose seed oils were characterized by an insecticidal activity against *Aphis fabae* and *Acyrthosiphon pisum* [27]. This activity was species, a region of collect and dose-dependent and the highest toxicity was recorded with *R. dumetorum* seed oils as compared to those of *R. canina*, *R. rubiginosa,* and *R. pomifera.* According to Ben Cheikh-Affene et al. [27], it was probably due to the oil richness of *R. dumetorum* on arachidic, stearic, palmitic, and oleic acids.

7 Conclusions

The edaphic characteristics differ according to the regions. The requirements of Rosa’s species for soils are different.*Rosa canina* is distributed on soils with balanced and clay texture and neutral to slightly acidic in Jendouba.*Rosa* × *alba* is growing in the same region. *Rosa moschata* grows on sandy or loamy soils with a balanced texture in cultivatingculture whereas *R. sempervirens* spreads over various soils which havedifferent spatial niches. *Rosa agrestis* and *R. micrantha*grow in sites characterized by calcareous soils.

The bioclimaticstagesfor the spontaneous growth of these species are humid, subhumid or upper semi-arid. Those species need rainfall (more than 400 mm.yr^{-1}),and they are glycophytes. Only *Rosa agrestis* and*R. micrantha*, which the rainfall is less than 400 mm.yr^{1}, need humid soils situated in watercourse of ravines.

The floristic compositionaccompanying*R. canina*, *R. sepmervirens,* and *R. moschata* is very rich inspecies. The climatic conditions and edaphic characteristics are favorable for this biodiversity. In contrast, the vegetative grouping of*Rosa* *agrestis* and*R. micrantha* is characterized by few species which are acclimated to these continental sites.

Rosa canina and *Rosa* × *alba* stations are located in northwestern of Tunisia, where the climate is humid, and the soils are neutral and under sandstone rock. *Rosa moschata,* a cultivated species requiring irrigation water, is distributed over plains in the north-east. *R. sempervirens*, spontaneous species, present a wider geographical area but in dry areas, it is confined in the watercourse. *Rosa agrestis* and *R. micrantha* are resistant to drought conditions in Central Tunisia, but with climatic changes characterized by an increase in aridity, these two species may disappear.

Rosa species and organs are characterized by a diversified set of essential oils and also by their richness on essential fatty acids, polyphenols, carotenoids, ascorbic acid… Their different extracts exhibited strong antioxidant activity, and rose hip oil could be used as a bio-insecticide agent. All these properties and characters are influenced by the growing conditions of the plant and also by used extraction system for metabolite isolation.

8 Recommendation

The investigations of *Rosa* species and accessions should be continued to search for the species reported in the Tunisian flora and not indicated in this study. Unexplored areas should be visited to complete the geographic distribution of *Rosa* species.

Rosa species are known as aromatic and medicinal plants and characterized by their richness on phytochemicals able to exhibit several biological activities. These characters could differ for the same species according to the site variation. For these reasons, it would be necessary to achieve *in-situ* conservation by creating rose gardensClimate change has an impact on some species that are at the limit of the extension of roses like in the central regions of Tunisia. It would be more appropriate to carry out *ex-situ* conservation and to preserve the seeds in the National Gene Bank and to encourage the cultivation of these aromatic and medicinal plants.

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Natural Mediterranean Plants Products: A Sustainable Approach for Integrated Insect Pests Management

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Abstract Plants produce two kinds of natural products commonly termed "primary metabolites", which are indispensable for plant growth and "secondary metabolites" that were previously considered as "waste products" without any physiological function for the plant. However, recent studies highlight their usefulness in plant defense against pathogens and insects herbivores and their role in beneficial insects attraction such us pollinators and auxiliaries. The secondary metabolites are classified into three different groups according to their biosynthetic origin: terpenoids, alkaloids and phenylpropanoids which each one was characterized with a specific mode of action against specific pest insects. Moreover, the natural products concentration depends largely in plant species. Recently, plant products are exploited for their benefit potential in crop protection thanks to their low toxicity to non-target organisms such as humans and auxiliaries, their effectiveness and environmental respect. The integration of plant products in pest management strategies would enhance sustainable agriculture and prevent loss in terms of both quality and quantity. This chapter provides an overview about the diversity of secondary metabolites in Mediterranean plants and their multifarious biological functions in crops protection against pests.

Keywords Secondary metabolites · Pest insects · Crop protection · Organic agriculture

1 Introduction

"Land plants and insects have coexisted for more than 400 million years" [1]. In co-evolution, both have evolved strategies to avoid each other's defense systems. This coexistence between plants and insects has resulted in the development of

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a specific defense system in plants able to recognize the exogenous molecules or signals. To limit the herbivores damages, they produce specialized morphological structures or secondary metabolites and proteins with toxic, repellent, and/or anti-nutritional effects on the herbivores [2]. Direct and indirect defense are tow kind of defense mechanisms that can be used by attacked plants. Both defense mechanisms may be present constitutively or induced after damage by the herbivores. Indirect defenses include chemical and ecological process influencing the plant–herbivore interactions. It can be mediated by the emission of volatile compounds attracting the specific natural ennemies by providing nutrition and habitat [3]. Direct defenses are mediated by physical barriers that affect the herbivore's biology through the developpement of trichomes, spines, thoms, cuticule and lignified cell walls or by chemical barriers like the production of toxic molecules such as terpenoids, alkaloids, phenols [3, 4]. These last products are named secondary metabolites; they act as anti-appetant compounds againt herbivores without affecting the plant growth [5]. However, secondary metabolites not only defend the plants from different stresses, but also increase their fitness [6]. Study on secondary metabolites lead to the identification of new molecules involved in plant defense against herbivores and their mode of action will be discussed below.

2 Plant Secondary Metabolites

A broad variety of organic compounds known as primary and secondary metabolites are synthesized by plants. Primary metabolites are compounds are associated with photosynthesis, respiration, and growth and development. However, secondary metabolites are related to the interaction of plant with its external environment, regardless of plant or animal species (Herbivores, auxiliaries) [7] and to defend itself against attacks by pathogenic pests and micro-organisms [8, 9]. The production of secondary metabolites in high quantity can offert to the plant more resisitance, but it can reduce its growth and reproduction [10, 11]. These metabolists can not be synthetised by all plant species like primary metabolites but it can specific for one species or to group of species taxonomically closed [12]. The nature and quantity of these metabolites are variable between families and plant species showing resistance to pest attack. More than 2000 species of plants belonging to the families of Meliaceae, Rutaceae, Asteraceae, Annonaceae, Labiatae, Lamiaceae and Canellaceae are rich in secondary metabolites with insecticidal activity [13–18].

Based on their biosynthetic origins, plant secondary metabolites can be divided into three major groups: (i) terpenoids, (ii) alkaloids and (iii) Phenylpropanoids.

2.1 Terpenoids

Terpenoids are a group of secondary metabolites synthesized by the plant from acetyl-CoA or glycolytic intermediates. They have been prized for their essential oils and their use as fragrances for over two thousand years [19, 20]. More than 40,000 structures are recognized with different functions. Terpenoids are therefore defined as a specific group of natural products based on hydrocarbons that have a structure that can be hypothetically derived from isoprene, consisting of five carbon atoms (C5) [21]. The most recognized terpenoids are the monoterpenes (C10) that can have acyclic structures such as Myrcene, Geraniol, and Linalool and cyclic one like Menthol, Camphor, Pinene, and Limonene [22], the sesquiterpenes (C15) which exist in aliphatic, bicyclic, and tricyclic frameworks [23], most monoterpenes and sesquiterpenes are components of the plant essential oil, the isoprenes (C5) are made of one five-carbon unit and are the simplest of all terpenoids. They are emitted from the leaves of many plants and contributes to the natural haze [24]. Based on the carbon number we can find: diterpenes (C20), that are considered to be resins because of their higher boiling points [25]; the triterpenes (C30) that are widely distributed among plant resins, cork, and cutin, and the common known groups are steroids, saponins, sterolins, and cardiac glycosides, among them the azadirachtin, a powerful insect antifeedant derived from seeds of the neem tree[26]. The tetraterpenes (C40) the carotenoids and terpenes with even more isoprene units are classified as polyterpenes [27].

Terpenoids act as a primary defense barrier against pathogens and are considered a key to decoding the insect-host interaction [28]. Also, they are the most metabolically diverse class of plant bioactive natural products. They act as antifeedants, repellents, toxins or as an insect growth regulator [29].

Essential oils are a mixture of volatile monoterpenes and sesquiterpenes that can have toxic and repellent activities on target insects. In fact, monoterpenes produced by conifers, such as pine and fir are toxic to several insects, including numerous bark beetle species [30]. The phytoecdysones isolated from *Polypodium vulgare* (common fern) are steroids that disrupt the insect molting du to its similarity to molting hormones [31]. Similarly, some terpenoid amide derivatives can act as insect juvenile hormone analogs [32]. Monoterpenes such as α or β pinenes, camphor,1,8-cineole, and terpinen-4-ol were the most frequently found components in most plant essential oils that had a high insecticidal effect in different coleopteran stored products [33].

2.2 Alkaloids

Alkaloids are compounds that contain nitrogen (structurally derived from ammonia) as part of their structure [22]. They are the widely distributed bioactive natural products. More than 15,000 different alkaloids are found in 20% of all vascular plants. Leguminosae, Liliaceae, Solanaceae and Amaryllidaceae are the richest families on alkaloids [1]. Many alkaloids are directly derived from the aromatic amino acids, phenylalanine, tyrosine, and tryptophan. They are known for their metabolic effects in mammals. Alkaloids (caffeine, nicotine, morphine, strychnine and cocaine) extracted from the plant are used for poisons, narcotics, stimulants, and medicines for several thousand years, and have evolved as defense against pest insect [4]. The authentic alkaloids are biosynthesized from amino acids in the roots and stored in the aerial part plant [34].

2.3 Phenylpropanoids

Phenolic compounds are one the most common secondary metabolites synthetized by plants. They are important components of many essential oils. Phenolic compounds participate in plant pigmentation, growth, reproduction, resistance to pathogens and for many other functions [35]. Regarded structure, phenylpropanoids contain a three-carbon side chain attached to a phenol. They have been classified on: "C6 (simple phenol, benzoquinones), C6-C1 (phenolic acid), C6-C2 (acetophenone, phenylacetic acid), C6-C3 (hydroxycinnamic acids, coumarins, phenylpropanes, chromones), C6-C4 (naphthoquinones), C6-C1-C6 (xanthones), C6-C2-C6 (stilbenes, anthraquinones), C6-C3-C6 (flavonoids, isoflavonoids), (C6-C3)2 (lignans, neolignans), (C6-C3-C6)2 (biflavonoids), (C6-C3)n (lignins), (C6)n (catechol melanins), (C6-C3-C6)n (condensed tannins)" [36].

Commonly, the role of phenolic compounds in defense is related to their antibiotic, antinutritional or unpalatable properties [35]. In fact, on phytophagous insects many flavonoids affect the behaviour, development and growth of a number of insects [37, 38]. They can act as feeding deterrents compounds at low concentrations. However, some other are feeding stimulants for the boll weevil, *Anthonomus grandis*, [39], or "oviposition stimulants of a Citrus-feeding swallowtail butterfly, *Papilio xuthus* L." [40].

3 Secondary Metabolites in Mediterranean Plants

"Humans have been traditionally using plants in order to protect crops" [41]. In the nineteenth century, several active molecules were extracted from plants such as nicotine from Papilionidae, and pyrethrum from *Chrysanthemum* (Asteraceae) but they have appeared to be toxic to mammals and chemically unstable respectively. After the Second World War, Azadirachtin a new compound extracted from the tropical tree: Azadirachta indica (Meliaceae) or neem, appear to be efficient in insect control [42]. The second strand of research was the looking at the use of plant material for crop protection. The Mediterranean flora presents numerous species belong to many botanical families processing an insecticidal activity. The investigation of Tunisian species leads to the identification of polyacetylene spiroketol

Table 1 Mediterranean plants with insecticidal proprieties and their main compounds

Family	Species	Origin	Active extract	Main compound (%)	Target insect	Reference
Apiaceae	*Anethum graveolens*	Egypte	Essential oil	β-phellandrene (24.88); Dill ether (14.85); carvone (14.5) p-cymene (14.38); liminene (11.92); α-phellandrene (8.21)	*Ephestia kuehniella* and *Tribolium castaneum*	[49]
Asteraceae	*Artemisia herba-alba*	–	Etheric extract	terpenes	*Myzus persicae*	[48]
	A. herba-alba	Tunisia	Essential oil	Camphor (11.48), 1,8 cineole (19.59), Alpha-pinene (5.4); camphene (2.63), and borneol (2.29)	*Orysaephilus surinamensis* and *T. castaneum*	[50]
	A. absinthium	Tunisia	Essential oil	beta-thujone (22.72), Camphene (2.37)	*O. surinamensis* and *T. castaneum*	[50]
	Chrysanthemum grandiflorum	Tunisia	Essential oil	α-humulene (18.4), β-caryophyllene (17.1), and caryophyllene oxide (14.5), α-pinene (16.8), α-cadinol (7.5), and n-tetracosane (7.5)	*Tribolium confusum*	[44]
	C. macrotum	Tunisia	Methanolic extract	polyacetylene spiroketol enol ether	*Spodoptera littoralis*	[43]
	Senecio lopezii	Spain	50% methanol extract	–	*T. castaneum*	[51]
Chenopodiaceae	*Anabasis hispanica*	Spain	Hexane extract	–	*T. castaneum*	[51]

(continued)

Table 1 (continued)

Family	Species	Origin	Active extract	Main compound (%)	Target insect	Reference
Labiatae	*M. pulegium*	Algeria	Essential oil	Pulegone (70.66; 70.4), neo-menthol (11.21; 13.4), menthone (2.63; 2.7), cis-isopulegone (2.33), Menthol (1.5) and neo-menthol acetate (3.5)	*Sitophilus granarius* and *Rhyzopertha dominica*	[52, 53]
	Mentha pulegium	Morocco	Essential oil	Pulegone (66.5), eucarvone (5.8), caryophyllene (3.9)	*Mayetiola destructor*	[54]
	M. rotundifolia	Algeria	Essential oil	trans-piperitone epoxide (30.2), piperitone oxide (8.7), thymol (4.5), germacrene D (3.5) and terpinen-4-ol (2.7)	*R. dominica*	[53]
Lamiaceae	*Lavandula angustifolia*	France	Essential oil	–	*S. littoralis*	[55]
	Melissa officinalis	Spain	Essential oil	–	*S. littoralis*	[55]
	Origanum compactum	Morocco	Essential oil	Carvacrole (58.1; 35.1); p-Cymene (11.4; 22.5); Thymol (9.0; 20); δ-Terpinene (7.1; 7.1)	*S. littoralis*; *M. destructor*	[54–56]

(continued)

Table 1 (continued)

Family	Species	Origin	Active extract	Main compound (%)	Target insect	Reference
	Origanum majorana	Morocco	Essential oil	Linalool (27.2); terpene-4-ol (17.1; 17,08); δ-terpinene (9.7); α-terpinene (6.3); Trans Sabinene hydrate (26, 64) and O-Cymene (6, 29)	*M. destructor*; *Bruchus lentis*	[54, 57]
	Rosmarinus officinalis	Algeria	Etheric extract	terpenes	*M. persicae*	[48]
	Salvia aucheri subsp. blancoana	Morocco	Essential oil	Camphor (57.3), camphene (6.3), α-pinene (4.1) and (E)-caryophyllene (5.4)	*T. castaneum*	[58]
	salvia officinalis	Morocco	Essential oil	α- hujone (20, 52), Eucalyptol (12, 39) and γ-Gurjunene (11, 13)	*B. lentis*	[57]
	Thymus algeriensis	Tunisia	Essential oil	α-terpinyl (20.1), camphor (10.5); 1,8-cinèole (10.3)	*T. castaneum*	[59]
	Thymus capitatus	Tunisia	Essential oil	Carvacrol (81.1)	*T. castaneum*	[59]

(continued)

Table 1 (continued)

Family	Species	Origin	Active extract	Main compound (%)	Target insect	Reference
Lauraceae	*Laurus nobilis*	Tunisia, Algeria, Morocco	Essential oil	1, 8-cineole (24.55; 34.62; 38.86), linalool (17.67; 12.57; 9.45) and isovaleraldehyde (9.65; 8.82; 10.47), α-pinene (2.52; 4.58; 4.34), α-terpineol (1.29; 0.90; 5.83), eugenylmethylether (12.40; 2.84; 3.93), β-pinene (1.39; 1.95; 1.92), spathulenol (1.12; 1.66; 0.16) and β-myrcene (0.3; 0.87; 0.80)	*R. dominica*, *T. castaneum*	[60]
Liliaceae	*Allium sativum*	Egypte	Essential oil	trisulfide, di-2-propeny (49.6); disulfide, di-2-propenyl (37.2); trisulfide, methyl 2-propenyl (5.6)	*E. kuehniella* and *T. castaneum*	[49]
	Asphodelus fistulosus	Spain	Hexane extract	–	*T. castaneum*	[51]
	Ocimum basilicum	Egypte	Essential oil	Linalool (52.6); Methyl chavicol (11.8); camphor (1.2)	*E. kuehniella* and *T. castaneum*	[49]
	Urginea maritima	Spain	Ethanolic extract	–	*T. castaneum*	[51]
Myrtaceae	*Eucalyptus camaldulensis*	Algeria	Etheric extract	terpenes	*M. persicae*	[48]

(continued)

Table 1 (continued)

Family	Species	Origin	Active extract	Main compound (%)	Target insect	Reference
	E. lehmani	Tunisia	Essential oil	α-pinene (31.61), Camphene (8.72), 1.8-Cineole (34.56), α-Terpineol (6.82)	*T. castaneum*, *R. dominica* and *Callosobruchus maculatus*	[61]
Pinaceae	*Pinus brutia*	Turkey	Essential oil	α-pinene (21.39), β-pinene (9.68), and caryophyllene (9.12)	Eggs of *E. kuehniella*	[62]
	P. pinea	Turkey	Essential oil	α-pinene (25.40), β-pinene (9.69), and caryophyllene (4.81)	Eggs of *E. kuehniella*	[62]
Rutaceae	*Citrus aurantium*	Tunisia	Essential oil	limonene (87.523); Linalool (3.36); myrcene (1.628)	*Tuta absoluta*; *Bemisia tabaci*	[63, 64]
	Ruta chalepensis	Tunisia	Essential oil	2-undecanon (48.28) and 2-nonanon (27)	*T. castaneum*	[65]
Scrophulariaceae	*Bellardia trixago*	Spain	Acetone and 50% methanol extracts	–	*T. castaneum*	[51]
Solanaceae	*Cestrum parqui*	Tunisia	Saponic extract	–	*Schistocerca gregaria*, *S. littoralis*, *T. confusum; Culex pipiens*	[45]

(continued)

Table 1 (continued)

Family	Species	Origin	Active extract	Main compound (%)	Target insect	Reference
Zingiberaceae	*Zingiber officinale*	Egypte	Essential oil	Zingiberene (14.0); Sabinene (12.0); Camphene (11.9); geranial (10.0); γ-terpinene (5.4) 1,8-cineole (5.3); α-pinene (4.1); Geraniol (2.6) α–terpinene (1.7)	*E. kuehniella* and *T. castaneum*	[49]

enol ether from *Chrysanthemum macrotum* toxic to *Spodoptera littoralis* [43]. Also *Chrysanthemum grandiflorum* essential oil rich in sesquiterpenes (β-caryophyllene 17.1% and α-humulene18.4%) was active against *Tribolium confusum* larvae causing high toxicity and anti-feeding effect [44]. Moreover, the study of *Cestrum parquii* saponic extract affects "significantly the survey of *Schistocerca gregaria*, *Spodoptera littoralis*, *Tribolium confusum* and *Culex pipiens*" [45]. In the same way, Perez and Pascual-Villalobos [46] demonstrated the anti-appetizing and bio-insecticidal activity against *T. castaneum*, *Acanthoscelides obtectus* (Coleoptera: Bruchidae) and *Bemisia tabaci* (Hemiptera: Aleyrodidae). Also, rosemary oil is recommended for control of aphids, Coleoptera, whitefly, mites, thrips and noctuid larvae [47].

Recent studies on etheric extract of *Artemisia herba-alba*, *Eucalyptus camaldulensis* and *Rosmarinus officinalis* highlights a significant insecticidal activity effect on *Myzus persicae.* The phytochemical screening of this extract showed its richness in terpenes [48] (Table 1).

4 Mode of Action Against Pest Insects

4.1 Anti-feeding Activity

This activity gives the insect the chance to feed from the host plant, but the amount of taked food decreases until the insect dies of hunger. The most responsible compounds are terpenes isolated from medicinal plants indigenous to Africa and India. Moreover, the anti-feeding activity is more important in fresh leaves than the dry ones. This asserts that these substances are volatile [66].

4.2 Repulsive Activity

Insects are repelled from the treated plant without necessarily eating. The use of repellent plants has been known for a long time, but it did not have much importance to develop it. The responsible compounds for this activity have unpleasant or irritating odors. In this context, garlic and pepper are among the best known plants. Also, fennel (*Foniculum vulgare*), rue (*Ruta graveolens*) and eucalyptus (*Eucaliptus globolis*) are commonly used to repel tissue mites [66]. As demonstrated by Isman [67–69] and Isman et al. [70], these kinds of essential oils prevent *Spodoptera litura* and *Myzus persicae* larvae from becoming closer to food.

Among essential oil compounds, terpenes are considered for their repellent potential, i.e. both terpineol and 1,8-cineole offered complete protection from *Culex pipiens* Molestus [71].

4.3 Toxic Activity

4.3.1 Disturbance of the Nervous System

This effect can be due to the extended opening time of the sodium channels causing the lengthening of the membrane depolarization, veratrine, a mixture of alkaloids containing cervadin, veratridine, sabadillin, sabadine and corvine, is responsible for this mode of action [72]. The same action is observed for the pyrethrum compound [73]. As a result, the insect exhibits hyperactivity called "Knock Down" phenomenon [74]. The same toxicity can also be a result of alkaloid (nicotine) acting on the acetylcholinesterase in the cholinergic synapse causing stimulation followed by depression of the vegetative ganglia and motor nerve endings in the striated muscles and central nervous system. Insect death occurs by paralysis of the respiratory muscles [75–77]. Others alkaloids (Ryana) cause an alteration of the nerve impulse conduction at the level of the calcium channels. This alteration causes permanent muscle contraction, which can lead to paralysis [74].

4.3.2 Disturbance of the Respiratory System

This action is associated with inhibition of the insect's ability to utilize oxygen by blocking the electrons flow between the iron-sulfur center of complex I and the ubiquinone binding site [77]. The main product responsible for this action is rotenone extracted from the roots or seeds of the genera Derris, Lonchocarpus and Tephrosia. It has been used for centuries as an arrow poison to paralyze fish [78, 79]. This substance is easily biodegradable, moderately toxic to warm-blooded animals, not very toxic to bees [79] and very toxic to fish with $LD50 = 132$ mg/kg [80].

4.3.3 Disruption of the Endocrine System

This action is due to the trouble of ecdysteroids synthesis by inhibiting the release of the prothoracotropic hormone produced by neurosecretory cells [67, 81] that cause the disturbance of exuviations and the reproductive cycle [82] by inhibition of sperm formation and delaying vitellogenesis in *Schistocerca gregaria* and *Locusta migratoria migratoria* [83–86]. The main responsible products are azadirachtin a tetranortriterpenoid limonoid extracted from the seeds of *Azadirachta indica* A. Juss [79] and Gibberellins phytohormones that are not toxic to mammals and auxiliary insects [80].

4.3.4 Growth Regulation

This mode of action is owing to semiochemicals and phytoecdysteroids, two plant natural products [77]. In fact plants producing semiochemicals can be used as a trap to control insects. Among these plants, the genus *Chrysanthemum* emits a substance called "chrysanthenone" attractive to thrips [87]. However, phytoecdysteroids are ecdysone analogues of plant origin [88], found in certain fungi, and Pteridophytes, some Gymnosperms and Angiosperms [89]. These phytoecdysteroids compete with the ecdysone site of action [90] and result in an anti-appetizing activity in the *Choristoneura fumiferana* larva [91] and moulting characterized by the persistence of the cephalic capsule [92]. Also, deficiency of tanning of the new cuticle is observed in *Bombyx mori* [90] and structural malformation of the endocuticle in other Lepidoptera [93]. This last action is pronounced during the last larval stage [91].

5 Conclusion

Plants produce a great variety of organic compounds used for their growth and development, reproduction, defense against attack by many herbivores. Most natural products can be classified into three major groups: terpenoids, alkaloids, and Phenylpropanoids compounds. Many mediterranean plants belong to the families of Apiaceae, Asteraceae, Labiatae, Lamiaceae, Liliaceae and Rutaceae are rich in secondary metabolites characterized with insecticidal activity against many agricultural pests (*T. castaneum*, *Bemisia tabaci*, *S. littoralis*….). The mode of action of these compounds is various and depends on nature of compound: some terpenes have an anti-feeding and repulsive activity, the other one is toxic by disturb the nervous, respiratory and endocrine systems and interfert with the regulation hormones causing insect death.

In the aim of plant protection many practical applications can be preceded. Biotechnological approaches can increase selectively the amounts of defense compounds in crop plants, thereby reducing the need for costly and potentially toxic pesticides. In the same way, genetic engineering can be utilized to increase the yields of active compounds.

6 Recommendations

Secondary metabolits can be recommended as an ecochemical approach to control herbivory insects in organic agriculture, thanks to their efficiency against target organisms, their biodegradibility and their safety for the environnement. Indeed, such products can be used as fumigants against stored product pests and fungi and as chemiochemicals by disturbing insect behavior and killed them. Essential oils can contain also chemosterillant compounds affecting insect reproduction and maintain them a low damage threshold. This novel concept of controlling insect pests in organic agriculture by using plant natural products could apply to other agricultural systems and different insect species. Thus, further studies should be focus on the development of specific herbivory insect secondary metabolite in order to improve knowledge about the insect metabolism of secondary metabolites and their mechanisms.

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Invasive Alien Plants Management in Tunisia

Najla Sayari and Mounir Mekki

Abstract The literature on biological invasions has grown rapidly since the mid-twentieth century as scientists, managers, policy makers, and the public have become increasingly aware of the many applied issues of managing invasive species, as well as the fundamental ecological questions raised by biological invasions. Tunisia, as any other countries in the world, is home to several alien plants introductions, some of which may become invasive, which justifies the urgent need for the implementation of a national strategy to manage plant invasion. Our researches are performed to study, test and evaluate methods and tools in attempt to deal with management of invasive alien plants in Tunisian ecosystems. The objectives of our research program are: (i) assess the current state of knowledge relevant to IAP management (ii) inventor and monitor potentially invasive plants already established in the country (iii) provide methods and tools to manage *Solanum elaeagnifolium* Cav.

Keywords Invasive alien plants · Management · *Solanum elaeagnifolium* · Tunisia

1 Introduction

Although not new, the phenomenon of biological invasions accelerated on a global scale in the latter half of the twentieth century [1–3]. The accelerating rates of international trade, travel, and transport have led to the progressive mixing of biota from across the world and the number of species introduced to new regions continues to increase [4]. Some introductions have led to dramatic declines in native animal and plant species and the functioning of ecosystems [5]. Several international agreements, including the International Plant Protection Convention (IPPC) and the Convention on Biological Diversity (CBD), recognize the negative impacts of invasive alien species (IAS) and reflect the growing concerns of policy-makers, scientists, stakeholders and society [6, 7].

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The Strategic Plan for Biodiversity in CBD included a specific target (Aichi Target 9) related to IAS and states that "*by 2020, invasive alien species and pathways are identified and prioritized, priority species are controlled or eradicated and measures are in place to manage pathways to prevent their introduction and establishment"* [8]. Tunisia, as a signatory country of CBD, is engaged to support the achievement of Target 9. There is, however, reluctance to propose a national management plan of IAS. Recognizing the need to generate technical tools and relevant information on IAP to prevent their introduction, eradicate new introduced populations and control naturalized IAP, our researches are performed to study, test and evaluate methods and tools in attempt to deal with management of IAP introduced and established in Tunisian ecosystems.

This chapter focus on biological invasion process and impacts, presents the main components of an effective IAP management scheme and proposes methods and tools that can be integrated into a national plan dedicated to management of *Solanum elaeagnifolium* Cav. in Tunisia.

2 Biological Invasions

On a geological time scale, biological invasion is "natural" phenomenon which happens when an organism arrives somewhere beyond its previous range [9, 10]. However, with the advent of agriculture and long-distance trade man has taken an increasingly active part in this phenomenon and become the main contributor, not only by deliberately or unintentionally transporting propagules, but also by altering ecosystems, making them vulnerable to invasions [11].

The use of simple terms to articulate ecological concepts can confuse ideological debates and undermine management efforts. This problem is particularly acute in studies of non- indigenous species, which alternatively have been called 'exotic', 'introduced', 'invasive' and 'naturalized', among others [12].

A variety of contentious terms are used to describe species that are introduced outside of their historical biogeographic range [13, 14], but for the purposes of this paper we will categorize them into four classes:

- **Alien plants:** (Synonymes: allochtonous, introduced, non-indigenous, exotic, xenophytes). Plant *taxa* in a given area whose presence is due to intentional or unintentional human involvement [13].
- **Naturalized plants:** (Synonym: established). Alien plant that sustain self-replacing populations without the direct intervention of people, through the recruitment of seeds or ramets capable of independent growth [13].
- **Invasive plants:** A subset of naturalized plants whose establishment and spread threaten ecosystems, habitats and species [15].
- **Weed:** Species that has a perceived negative ecological or economic effect on agricultural or natural systems [16].

2.1 *Invasion Process*

Since its introduction to a new territory, the plant taxon required to overcome various abiotic and biotic barriers. Accordingly, not all alien plants become invasive. Many that are accidentally or intentionally introduced do not survive in the new environment, and of the ones that do survive, few become invasive. Thus, the biological invasion process follows a phase sequence "introduction—acclimation—naturalization—invasion" [12, 14, 17]. Phases of the process can be defined on the basis of the relevant barriers.

- **Introduction** means that the plant or its propagule has overcome the geographical barrier to conquer new habitats [14, 18]. The movements of individuals can be the fact of the action of the Man voluntarily or accidentally. But they can also occur naturally because of the physical, punctual or continuous connections that can exist between two geographic areas [19, 20].
- **Acclimation** is the overcoming of an environmental barrier that implies the success of the introduced species to survive and withstand the prevailing climatic conditions in the region of introduction [21, 22].
- **Naturalization** is the overcoming of a reproductive barrier that implies the success of the acclimated species to reproduce in the natural environment without or despite human intervention [3]. Many introduced plant *taxa* survive as casuals that can reproduce sexually or vegetatively but fail to maintain their populations over longer periods.
- **Invasion** is the overcoming of a dispersal barrier and corresponds to a phase of proliferation and geographic expansion in disturbed, semi natural or natural environments [14]. In general, a lag time is observed between the introduction of an alien plant and the manifestation of its impact on the host ecosystem. Lag times are typically defined as a period of several years to several decades between the introduction and establishment of an exotic and its period of rapid geographic range expansion [23]. Better knowledge of lag phases could inform efforts to assess the risks and predict impacts posed by potential invaders [24].

Only a very small percentage of the species that are effectively introduced after overcoming a geographic barrier go on to become invasive and to have a negative impact on the environment and on human activities [25]. According to Williamson [3], 10% of introduced plant species are found in the wild, 10% of them will establish, and 10% of them will become invasive (10 rule).

2.2 *IAP Impacts*

Increasing trade and tourism in recent decades may have led to increasing numbers of alien plants. Climate change may also play a role in the spread of these species, making some areas more favorable to the introduction and establishment of alien plants [8, 26]. An ecosystem can support these changes as long as all the original key components are not negatively affected.

Plant invasions impact the structure, composition and function of natural and semi-natural habitats [27]. IAP may displace native biota by out competing indigenous plant communities that result in endemic species loss, habitat destruction [28, 29] and disruptions of mutualistic networks such as pollination and dispersal [30]. They may also alter the evolutionary pathway of native species by niche displacement and ultimately extinction [31]. Other impacts include effects on the genetic variation and eroding gene pools of native populations via hybridization [22]. In some cases, ecosystems altered by IAP may be less able to provide important 'ecosystem services' which support human activity [5, 32]. Thus, plant invasions cause significant impacts on a number of economic activities, for example by provoking damages to infrastructure, landscapes and agriculture [33]. Such impacts can have strong socioeconomic consequences.

IAP can have a prominent impact on human health, by being specific disease vectors or by posing a direct health threat [33]. Examples of human health problems caused by IAP include eye and skin lesions upon contact with giant hogweed "*Heracleum mantegazzianum* Sommier and Levier" [34], rhino-conjunctivitis and asthma through contact with common ragweed "*Ambrosia artemisiifolia* L." allergenic pollen [35]. Species like tickberry "*Lantana camara* L." and floating water hyacinth "*Eichornia cressipes* (Mart.) Solms" provide habitat for mosquitoes. There are increasing instances of mosquito borne diseases where these species have invaded [28].

3 IAP Management

The challenges of managing IAP are urgent, and are growing in scale with globalization and climate change. The problem is global, and managing it requires international as well as local action [36].

3.1 Global Context

IAP Management requires action by a wide range of stakeholders, at all levels and across professional and other boundaries. International conventions reflect the growing awareness of this issue globally.

- **IPPC**
  In existence since 1950, it is implemented by its contracting parties via national and regional plant protection organizations. The objective of the Convention is to prevent the introduction and spread of pests and pathogens affecting both agricultural and wild plants [37].

- **World Trade Organization Sanitary and Phytosanitary Agreement (WTO–SPS)**
  The SPS Agreement deals with specific issues concerning human, animal and plant health, and lays out rules for coordinating policies. Sanitary and phytosanitary measures can take many forms, including requiring products to come from a disease-free area, inspection of products, or specific treatment of products. To improve the efficiency of the SPS Agreement, international standards are used in its operation: those of the IPPC for plants and of the World Organization for Animal Health for animals [38].
- **CBD**
  The CBD has been ratified by 189 countries including Tunisia. It provides that each contracting party shall prevent the introduction, control or eradication of alien species that threaten ecosystems, habitats or species. The CBD recommends that Contracting Parties give priority "to the development of strategies and action plans for the control of invasive alien species (IAS)" at different scales [31].

3.2 Management General Scheme

There is an intimate correlation between the detailed understanding of the invasion process and the implementation of an appropriate management strategy. Indeed, the invasions process has been divided into three major phases (introduction, establishment and invasion), each phase is linked to management priorities. The introduction is associated to prevention, the establishment to early detection and eradication, the spread to control and containment. The goal of such actions is the restoration of ecosystems to preserve or reestablish native biodiversity and functions [34, 39].

3.2.1 Prevention

It represents the first line of defense that offers the best cost-effectiveness against invasion by IAP [40]. The first important step to prevent IAP introduction is to identify plants with precedent invasive behavior in a given context and are at risk of becoming invasive in similar environmental circumstances [41, 42]. These species should be treated as potentially invasive and therefore require special attention.

Border controls and quarantine measures are often the first opportunity to respond to IAP incursions [34]. These procedures can be part of the Risk Management approach, which is an important tool for prevention, containment and control of biological invasions [43, 44].

3.2.2 Early Detection and Eradication

Rapid response should be consequent on early detection but, when IAP are rare, detection is compromised by low occurrence [17, 34]. The precautionary principle encourages action to be taken to eradicate potentially harmful IAP as soon as they are detected [45]. It is particularly appealing because the alternatives of containment or broadscale control require permanent, ongoing investment of time and money [45, 46].

3.2.3 Containment and Control

Containment should limit IAS spread either from an invaded region or alternatively exclude species from an uninvaded area. The success of containment strategies depends on the ability to detect new incursions either at the margin of existing IAP ranges or in new regions [34]. If an IAP is already widespread, then specific control program may be the only practical way of going on the offensive [42]. This management approach employs several complementary methods to control alien invasion. These methods can include biological control, improved land management practices, herbicides and mechanical methods [47].

Controlling or eradicating IAS is not a management goal in itself, but only one means to achieve higher goals, such as the conservation of biological diversity, protection of human health, and prevention of economic loss [48]. Elements of these goals might include habitat restoration, reintroduction of native species, preservation of relatively undisturbed ecosystems enabling natural succession rate and time, and establishment of sustainable use of ecosystem services for local people [42].

4 IAP Management in Tunisia

Tunisia is the northernmost country in Africa, covering 165,000 km^2. It lies between latitudes 30° and 38°N, and longitudes 7° and 12°E. It is bordered to the West by Algeria, throughout 965 km, and to the South East by Libya, throughout 459 km. It is separated from Europe by the Mediterranean Sea which spans about 1,300 km of coastline. Thus, by its geographical position which offers an opening on the Mediterranean Sea in the North and East, Tunisia is permanently exposed to the risks of IAP introduction. Numerous invasive and naturalized plant species have been reported in scientific publications [23, 49, 50]. These publications stimulate interest on biological invasion among researchers, managers and policy makers. To address the emerging threat of IAP a management strategy is becoming crucial.

The first step in any management strategy to control plants invasion is the compilation of a national and regional inventory of alien plant species [51, 52]. Such data compilation is of fundamental importance in the establishment of a national system of early detection and rapid response [47]. In the sections below we present a synthetic overview of the main results on the spontaneous alien flora inventory in Tunisia, as well as some methods and tools enable to manage one of the worst invasive plants (Solanum elaeagnifolium Cav. # SOLEL) in Tunisia.

4.1 Potentially IAP Inventory

National inventory of the Tunisian flora begun by Cuenod *et al.* in 1954 [53] and completed later by Pottier-Alapetite, in 1979 [54] and 1981 [55]. The vascular flora of Tunisia numbers 2162 species [56]. In our case we are interested in inventorying spontaneous alien plants. For the achievement of this objective we are based mainly on the national floras mentioned above, as well as the updated publications of Le Floc'h [49] and Nabli [56–58]. We cross-checked considering new flora records and field surveys.

4.1.1 *Taxa* Diversity and Structure

Data compilation totals 92 alien taxa including 68 genera, 82 species, 7 subspecies and 2 varieties. This spontaneous alien flora belongs to 33 families, with 80% *Dicotyledoneae* and 20% *Monocotyledoneae*. The most represented families in the Tunisian spontaneous alien flora are *Asteraceae* (15%), *Amaranthaceae* (14%), *Poaceae* (12%) and *Solanaceae* (9%). The genera that account for the highest number of alien entities are *Amaranthus* followed by *Erigeron* and *Cyperus*.

The most numerous alien taxa are therophytes (38%) followed by geophytes (35%) and phanerophytes (18%). Hemicryptophytes are represented only by one taxon. We counted also two taxa as therophytes/hemicryptophytes and five taxa as therophytes/geophytes (Fig. 1).

Therophytes dominance can be attributed to the fact that up to 90% of the alien taxa occur in disturbed habitats and they are mainly recognized, in Tunisia or in other regions of the world, as common weeds in cultivated fields, pasture and roadsides (i.e. *Abutilon theophrasti* Medik, *Agave americana* L., *Amaranthus retroflexus* L., *Datura stramonium* L., *Erigeron bonariensis* L., *Solanum elaeagnifolium* Cav., *Symphyotrichum squamatum* (Spreng.) Nesom and *Xanthium spinosum* L.). On the other hand, 10% of this alien flora occurs both in disturbed and natural habitats (i.e. *Ehrharta calycina* Sm., *Ipomoea purpurea* (L.) Roth, *Lamium amplexicaule* L. and *Lantana camara* L.).

The majority of the alien taxa have been introduced into Tunisia from the Americas (50%), followed by species of South and tropical African origin (13%) and Eurasian origin (11%). The provenance of the remaining species varies considerably, ranging from Europe to Australia, though the native ranges of many species introduced remain unknown (Fig. 2).

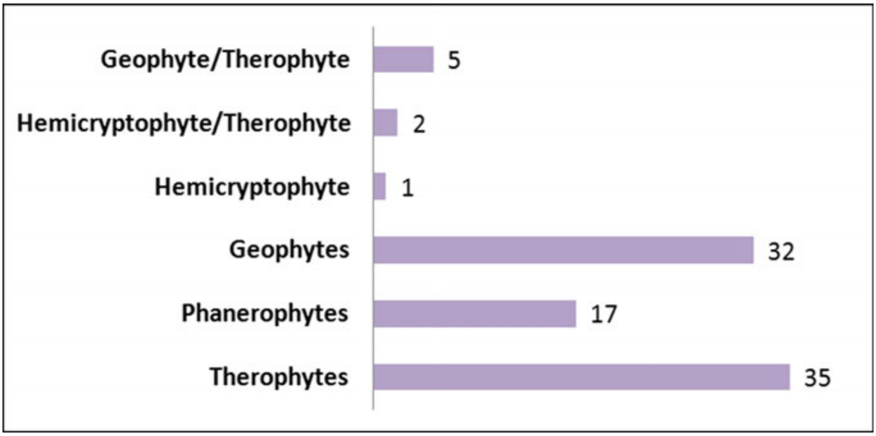

Fig. 1 Life forms of the spontaneous alien flora in Tunisia (Number of taxa) [50]

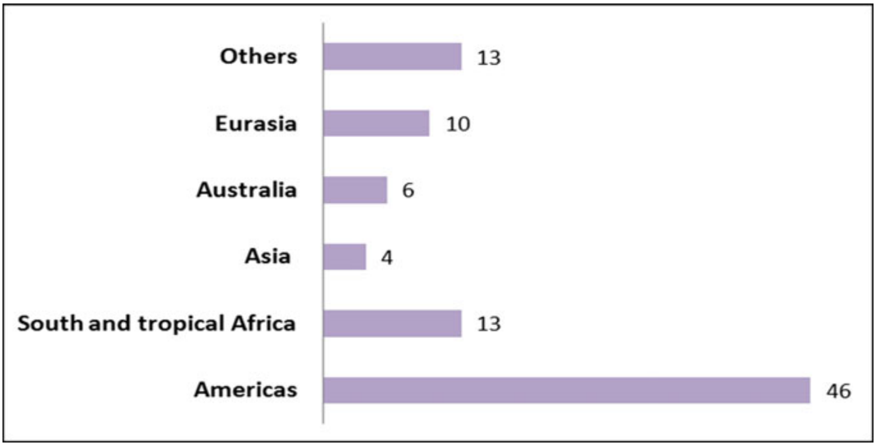

Fig. 2 Native range of the alien flora in Tunisia [50]

4.1.2 Alien Plant Status

According to Le Floc'h et al. [49], 34 alien *taxa* are naturalized in Tunisia, among them nine are categorized as weeds. Three alien plants (*Cardaria draba* (L.) Desv., *Crassula helmsii* Cockayne and *Solanum elaeagnifolium* Cav.) are invasive and one specie (*Verbesina encelioides* (Cav.) Benth. et Hook. fil. ex A. Gray) was newly detected in 2011 [23]. Four taxa are invasive in the Mediterranean Basin [59], 18 are invasive in Sardinia (Italy) [60]. *Solanum elaeagnifolium* Cav. is listed on the A2 EPPO IAP list of pests recommended for regulation and *Verbesina encelioides* (Cav.) Benth. et Hook. fil. ex A. Gray) is listed on the observation List [61]. Six other *taxa* (*Arctotheca calendula* (L.) Levyns, *Carpobrotus edulis* (L.) N.E. Br., *Cyperus esculentus* L., *Cyperus rotundus* L., *Paspalum distichum* L. and *Oxalis pes-caprae* L.) are listed on the IAP EPPO list [61]. In addition, three *taxa* (*Arundo Donax* L., *Lantana camara* L. and *Schinus terebenthifolius* Roddi.) are listed among the 100 World's Worst Invasive Alien Species [39] and five *taxa* are considered invasive in Europe (*Acacia saligna* (Labill.) Wendl., *Alternanthera sessilis* (L.) DC., *Echinochloa colona* (L.) Link, *Ipomoea purpurea* (L.) Roth, *Oxalis corniculata* L.) [62]. Therefore, about 40% of alien taxa in Tunisia are listed in IAP official lists of several countries and regions [59, 61, 62]. Hence, all these alien taxa are likely to become invasive in Tunisia.

4.2 Silverleaf Nightshade Management (Solanum Elaeagnifolium Cav. # SOEL)

SOLEL is native to Northeast Mexico and Southwest USA [62]. It is a summer growing perennial herb, reproducing by seed and from creeping perennial roots. Multiple reproductive strategies, high seed production, long flowering and fruiting periods, short juvenile period, deep and dense root system are main attributes that predisposes SOLEL to become an invasive weed [63].

4.2.1 SOLEL Status in Middle East and North Africa Countries

SOLEL is considered as one of the most widespread invasive weeds in the world [62, 64]. It is listed as a noxious weed in 21 USA states and since 2006 it has been listed as an EPPO A2 pest recommended for regulation [61].

In the Middle East countries SOLEL was unintentionally introduced in 1967 in Syria, in 1970 in Jordan and Iraq and in 2012 in Lebanon [65]. Syria remains the most highly invaded country where it is reported to occupy 27 562 ha.

In North Africa, the earliest introductions of SOLEL date back to1949 in Morocco and it is now considered the nation's most noxious weed [66] especially in irrigated fields [67]. Later, it was detected in 1956 in Egypt, in 1985 in Algeria and in 2014 in Libya [68].

In Tunisia, since 1985, SOLEL started to become a noxious weed [69]. The invaded area is increasing and this weed is becoming a potential threat to thousands of hectares of irrigated fields in arid and semiarid regions [63]. The most infested habitats and land-uses are roadsides, wastelands and summer crops. These infestations generate considerable crop yield losses [70]. Therefore, the implementation of a management plan for this invasive weed is fundamental.

4.2.2 SOLEL Management in Tunisia

Since 2005, Tunisia has increased its interest in the management of IAP and more specifically for SOLEL. The country has therefore solicited the support of the sub-regional office of the United Nations Organization for Agriculture and Food (FAO-SNE) to conduct a regional technical cooperation program (TCP/RAB/ 3102) on the management of IAP and in particular SOLEL (2008–2009). Other research programs were also conducted to support the implementation of an appropriate control approach against SOLEL [71]. In our case we propose methods and tools that can be integrated into a national plan dedicated to the management of SOLEL in Tunisia as an invasive plant and not as a common weed. Our research was launched to achieve the following objectives:

– Study biological traits that makes SOLEL invasive in a Tunisian semi-arid region,
– Map and monitor SOLEL at a local scale,
– Identify appropriate times for herbicide treatments to control SOLEL,
– Distinguish appropriate control approaches to manage SOLEL.

- **SOLEL biological traits in a Tunisian semi-arid region**

SOLEL grows in a wide range of environmental conditions. In its native range, it is well adapted to semi-arid regions with dry winters, wet summers and annual rainfall of 300–550 mm [72]. In Tunisia, it infests semi-arid Mediterranean climate [63]. SOLEL behavior (number of vegetative shoots, flowering shoots and fruit bearing shoots; number of sprouts within a radius of one meter from mothers' plants) was monitored during the period 2012–2015 at Chott-Meriem a coastal region, located in the Centre-East of Tunisia between 35°90′–35°99′ N and 10°50′–10°60′ E. Its climate is semi-arid with mild rainy winters and hot, dry summers.

This monitoring allowed us to conclude:

– SOLEL root fragments, buried in the soil, were able to generate new aerial shoots after a dormancy period up to 18 months,
– SOLEL life cycle is characterized by two periods of vegetative growth. The first in the spring, marking the resumption of vegetative growth of plants after winter dormancy, and the second in autumn, stimulated by fall rains. However, during the hot and dry summer vegetative growth regresses in favor of sexual reproduction (flowing and fructification) (Fig. 3).
– Once established, SOLEL sprouts emerge during the first year within a radius of 25 cm. Thereafter, the spatial propagation radius of each mother plant exceeds one meter.

These conclusions are able to guide us in the implementation of a SOLEL management program taking into account its growth stages (vegetative growth, flowering and fructification) and spatial invasion mechanism.

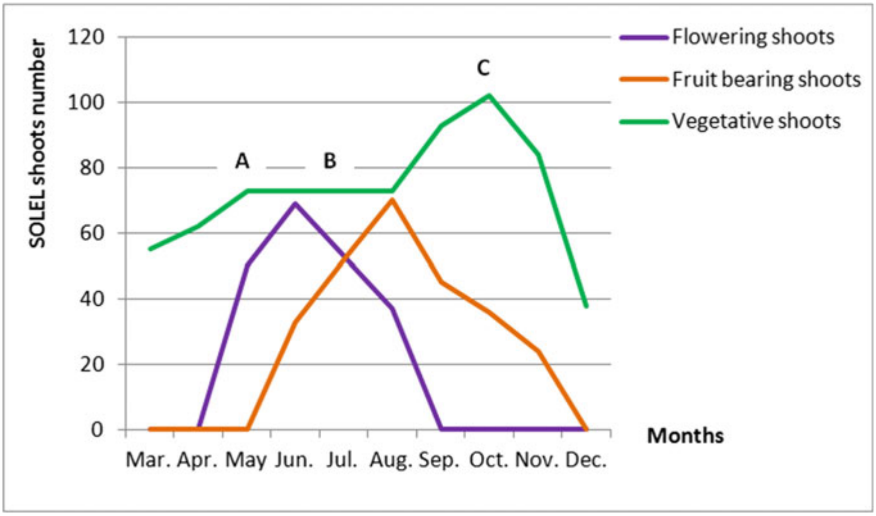

Fig. 3 SOLEL population dynamic recorded in 2013 and confirmed in 2014 and 2015 (A: first peak of vegetation after winter dormancy, B: vegetative growth cessation in favor of sexual reproduction (flowing and fructification), C: second peak of vegetation in autumn) [73]

- **Mapping and monitoring SOLEL distribution at a local scale**

Mapping invasive weeds distribution is considered the foundation for the development of a strategic long-term management plan to protect agro-biodiversity and prevent invasion of other noxious weed species [7, 74]. It allows characterizing the pattern of distribution of these plants, predicting their rate of spread and evaluating the relationship between their spatial extent and abundance [75]. In this context, SOLEL mapping, using the GPS/GIS technologies, in the irrigated land of Chott-Meriem (Tunisia) was conducted in 2008 and updated later in 2014 to estimate its rate of spread and characterize its distribution pattern within cultivated and uncultivated plots (fallows) and their borders.

Our study reveals that from 2008 to 2014 SOLEL occurence in the studied area increased by 50%. In fact, the number of infested plots evolved from 24 in 2008 (Fig. 4A) to 36 in 2014 (Fig. 4B). Consequently, the total surface of infested plots increased by 60%, it evolved from 123.5 ha in 2008 to 196 ha in 2014. Furthermore, along plot borders SOLEL occurrence increased 3.5 times. Indeed, 7 linear infestations were recorded along 1.5 km in 2008 (Fig. 4A) and 25 linear infestations were recorded along 4.8 km in 2014 (Fig. 4B). On the other hand, SOLEL distribution pattern characterization reveals that the patchy pattern was the most common distribution type for the weed which reflects a wide expansion of this species in the studied area and gives us an idea about its residence time in the study area.

These results confirm the ongoing colonization process of SOLEL and show that its control as a conventional weed, practice mainly adopted by the region's farmers, is inappropriate and that a specific management plan should be implemented. In fact,

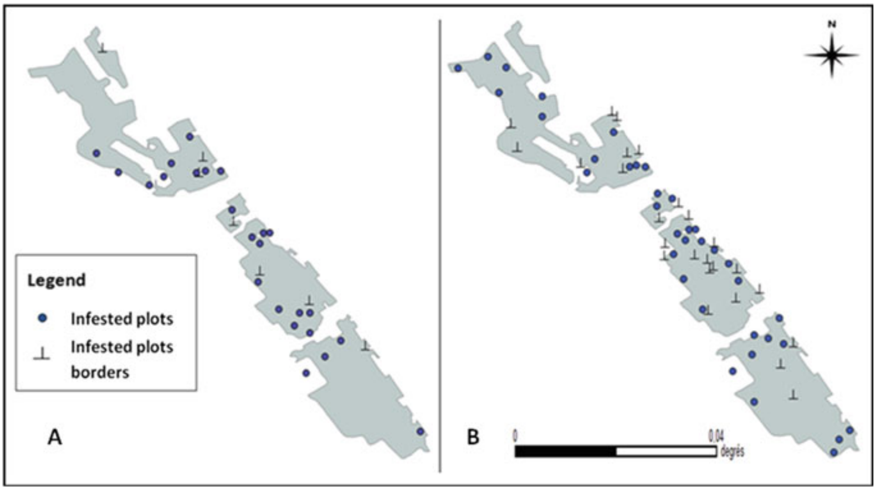

Fig. 4 SOLEL infestation progress in the irrigated land of Chott Meriem (Tunisia) from 2008 to 2014 (A: 2008; B: 2014) [76]

weed control and invasive alien plants management are two distinct approaches. In intensive agriculture, weed control is mainly a reactive approach, based on herbicide technology and aims to preserve crop yields. However, IAP management, based on a risk assessment scheme, is mainly a proactive approach which aims to prevent IAP introduction and establishment [71].

This study highlights also the importance of IAP mapping using the GPS/GIS technologies which offers a very useful tool to address management priorities and provide a baseline for future monitoring efforts.

- **Herbicide Treatments**

Over the decades a wide array of herbicides has been screened for efficacy [77]. According to Bouhache et al. [78] the maximum effect is achieved if the herbicide is applied in optimal conditions and at susceptible growth stage. Most foliar herbicides translocate, or move inside the plant, in the same direction as do non-structural carbohydrates (TNC) which are translocated from source (mainly leaves) to sinks (the rapidly growing or storage organs) in perennial plants.

Glyphosate, a foliar systemic phloem mobile, is the most widely used herbicide for postemergence weed control. It should have a good efficiency if its application coincides with the intense TNC migration to the root system [79].

Our study conducted from June 2012 to June 2013 consists to evaluate glyphosate activity, at a rate of 4.5 L.ha^{-1} (2025 g a.i. ha^{-1}), against SOLEL at three growth stages (full flowering, green berries and ripened berries). Herbicide activity was assessed to evaluate flowers, berries and sprouts numbers.plant^{-1} reduction. Further, SOLEL regeneration was scored next spring.

Results showed that glyphosate timing of application had a significant effect on berries number.plant^{-1} and the number of sprouts. 60 DAT a similarly trend in berries number.plant^{-1} reduction was noted after the glyphosate application at green berries (35%) and ripened berries (35%) stages. However, berries number.plant^{-1} was increased with 40% after the glyphosate application at full flowering stage. These finding are similar to those of Baye [80] who confirmed that SOLEL berries production was significantly reduced after the glyphosate application at flowering stage.

Next spring (June 2013) the maximum rise of sprouts number was recorded after the glyphosate application at full flowering stage followed by ripened berries stage and green berries stage. Therefore, glyphosate efficiency can reach its maximum if its application is done at green berries stage when the carbohydrates migration to the root system is optimal. These results are in agreement with several studies [78, 79] which documented that the maximum effect is achieved if the herbicide is applied at green berries stage, coinciding with the optimal period of carbohydrates reserves recovery.

These findings highlight that TNC evolution in SOLEL is a promising way for the chemical control of this plant. It showed clearly that glyphosate application at green berries stage reduce berries production. At this stage TNC migration to roots is optimal which lead a significant reduction on sprouts regeneration.

- **Recommendations for better SOLEL management**

SOLEL management experience in Tunisia allowed us to realize that the classical weed control approach is inappropriate against IAP [71]. Through our research studying SOLEL invasiveness, rate of extend, distribution pattern, and response to control approaches we can propose:

- The prevention of SOLEL spread to preserve uninfested areas and contain its invasion.
- In new infested areas, we recommend its eradication with cooperative actions among public authorities and field owners.
- In dense infested areas, we recommend the implementation of an integrated management plan that combines chemical and mechanical methods.
- Herbicides should be applied at the appropriate time. In fact, the maximum effect of systemic phloem mobile herbicide is achieved if it is applied to growth stages during which their mobility to the roots is maximal.
- A spring weeding is able to control SOLEL during the summer period. However, SOLEL regeneration was subsequently observed. Thus, a second weeding is necessary to maintain its density below 5 stems.m^{-2}, to prevent its fruiting and to preserve the moisture of the soil. The second weeding can be coupled with soil preparation for sowing or planting fall crops.

5 Conclusions

IAS pose a profound impact on humans as well as on the ecosystems as they can be a cause of heavy economic loss, in terms of reduced crop and livestock production, reduced native biodiversity, costs involved to control their rapid spread and impacts on human health. In order to control their spread, measures have to be taken at national and local level. Realizing the threat of biological invasion, more attention has been given on research, monitoring, control and management of invasive species in the recent years by global communities. The CBD calls for its signatory nations to prevent the introduction, control or eradication of those alien species.

Despite the increased interest given to IAP, monitoring and management of biological invasions is not yet a priority in Tunisia. Some works have been initiated but they are not well coordinated. On the other hand, there is no national strategy document for IAP management. The case study of SOLEL management in Tunisia confirms the ongoing colonization process of this invasive weed and shows that its control as a conventional weed is inappropriate. Thus, a national action plan to contain SOLEL spread in the Mediterranean region is urgently required.

Based on SOLEL biological traits and its invasion mechanism described above we could be able to prevent its spread and preserve uninfested areas. On the other hand, mapping SOLEL distribution using the GPS/GIS technologies should be developed to study the evolution of its infestation extend throughout the Tunisian territory. Additionally, SOLEL bioecological attributes and recommendations concerning its chemical and mechanical control as well as their appropriate application times should be integrated on a specific management program to succeed its eradication in newly infested area and its control and containment in dense infested areas.

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Study of the Effect of the Biochar Amendment on the Physic-Chemical Properties of a Soil Cultivated in Green Mint (*Mentha Viridis L.*)

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Abstract The use of aromatic and medicinal plants for therapeutic, cosmetic and culinary purposes is a very old practice. Given the advantages of these plants, several efforts have been directed towards improving their yields while guaranteeing satisfactory quality. Intensification of the crop is therefore a necessity which must be supported by the optimization of the factors of production of which the most important is the improvement of the physicochemical properties of soil. In this context, the study focuses on spearmint (*Mentha spicata viridis*), an annual herbaceous aromatic and herbal medicinal plant for aromatic, condimental, ornamental and medicinal purposes. The interest of this crop is mainly related to the commercial importance of its essential oil, which is among the ten most traded oils in the world. The latter is used in many industries, including pharmaceuticals, cosmetics, food and chemicals. Despite its socio-economic importance, its qualities in Tunisia do not yet meet the international norm for the use of chemical inputs (fertilizers, pesticides, etc.) for cultivation which negatively affect its production level because of the gradual decrease Of soil fertility as well physical as chemical during the last decades. Faced with these problems, the use of sustainable agriculture becomes an economically viable solution. Researchers in this field have developed studies that tend towards agriculture on a human scale, linked to a healthy soil and economical both in inputs and in means of production. Organic fertilization aims to protect and preserve the soil in the long term, thus it remains one of the techniques of sustainable agriculture. The latter must meet the needs of present generations without compromising the development of future generations, guaranteeing them the same opportunities for progress. Biochar and compost are two organic fertilizers rich in nutrients and necessary for crops. They guarantee better sequestration of carbon in the soil and optimize the majority of soil physicochemical parameters. While valorising them makes it possible to save inputs while respecting the environment. The mint fertilized with biochar gives the best yield of methanolic extract and contains the highest total polyphenol and flavonoid contents. Mint fertilized with biochar and compost separately demonstrates the highest anti-free radical activity and iron-reducing power.

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1 Introduction

Aromatic plants are of great importance because of their many uses especially their wealth in essential oils. These plants have been grown on all continents for a very long time for multiple uses. They are represented in many botanical families including the Lamiaceae family. The essential oils produced by these plants are very varied in their chemical composition. They are used in the manufacture of pharmaceutical, cosmetic and food products.

These plants are considered lucrative crops thanks to their essential oils which are very expensive and are in great demand.

Mint is a perennial or annual aromatic and medicinal herb in the world and can be grown for many years. The cultivation of mint would then allow producers to diversify cash crops, increase the receipts of agricultural products of the country and thus help the development of the rural economy. It would also provide income, almost all year round, to producers and diversify their sources of income.

On the other hand, in order for mint cultivation to produce the desired results, it is necessary to intensify production by bringing large quantities of fertilizer. In view of the benefits of aromatic and medicinal plants for both producers and the country, it is essential to increase the quantities and to improve the quality of the fresh material and the essential oil produced in order to support the production and satisfy the demand.

The intensification of culture is a necessity and this must be accompanied by research on the optimization of factors of production, the most important of which is the improvement of the physicochemical properties of soil.

The intensive use of mineral and chemical fertilizers has two types of consequences:

- Have health risks including the best known for the consumption of water rich in nitrate, resulting from nitrogen fertilization, or environmental risks such as pollution of drinking water, and also the contribution to global warming, due to strong gaseous emission, after fertilizer application.
- Highly reduce soil fertility, both physical and chemical; in fact, it gives plants fed by infusion of chemical fertilizers and soil that continues to degrade over time.

Faced with these problems, the use of sustainable agriculture becomes an economically profitable solution. This means that it must meet the needs of present generations without compromising the development of future generations, guaranteeing them the same opportunities for progress.

Sustainable agriculture is a reflection on the future of farms and more broadly on the life of the countryside of tomorrow. Researchers in this field have developed studies that tend towards human-scale agriculture, linked to a healthy soil that is economical in inputs and means of production. In this context, biochar and compost are the two organic sources to be used to offset the needs of the carbon crop and to conserve the soil for future generations.

Biochar and compost contain the nutrients and organic matter needed for soil and crops and ensure better carbon sequestration in the soil. To value them well makes it possible to save inputs while respecting the environment.

Our objective is to substitute mineral fertilization with the improved organic one (Biochar and compost) in order to obtain soil with good chemical, physical and biological fertility on the one hand and to improve the quality of the by-products of agricultural crops. on the other hand in order to have sustainable agriculture and ensure good food security.

2 Materials and Methods

An organic fertilization open field trial was conducted in the experimental station of the Higher School of Agriculture of Kef (ESAK), located 5 km south of the city of Kef, in the north-west of Tunisia. The governorate of Kef is located about 175 km from Tunis, 40 km south of Jendouba, 110 km north of Kasserine and 160 km west of Siliana. The region belongs to the upper semi-arid bioclimatic stage. It is a particularly harsh climate and has a continental character because of its remoteness from the sea. The winter is rigorous and the minimum temperatures are among the lowest in Tunisia. Snowfall is frequent on the heights around January. Jellies are frequent and late in the spring, and hail is also common, while in summer the plains are exposed to the warm continental winds and the sirocco.

The fertilization test was conducted according to a complete random block experimental.

The experimental trial was arranged within a completely randomized bloc design (CRBD) with 3 repetitions.

Before the installation of the test, a representative soil sample was taken from the plot using the zigzag method using a shovel. This sample was transported to the ESAK Soil Science Laboratory. It was dried in the open, crushed, and sieved to study the physicochemical properties of the soil.

The soil is little evolved of alluvial supply vertic. The analyzes show that our soil has a silty-sandy clay texture, a pH = 8.23, and an organic matter content MO(%) = 1.32. the concentration of mineral nitrogen, available phosphorus and exchangeable potassium respectively of the order of 8.38, 12.65 and 379.33 mg. Kg-1of soil.

The plot on which the spreading was divided into 12 elementary blocks each having an area of 0.6 m^2.

Four treatments were used; Witness (T), 600 g of Biochar (B)/0.6 m^2, 2 kg of Compost (C)/0.6m^2 and 2.6 kg Mixed (C + B)/0.6m^2.

The biochar used in this test comes from the traditional pyrolysis of wild acacia. This fertilizer was carefully buried. The test was installed from mint cuttings (*Mentha viridis*). Irrigation was controlled (even doses every day) and weeds were eliminated by hand.

Three months after the contribution of biochar, we did the first sampling of each elementary plot to study the physicochemical parameters of the soil. Ten days after the first sampling, the first cut of plants was carried out in order to extract the essential oils and to measure their antioxidant and antimicrobial activities. After two months, the second sampling was done.

Bulk density measurements were done by the cylinder method. Soil samples were collected from the surface horizon to determination of the true density as the pycnometer method. Soil porosity was calculated by the formula % P = (1-bulk density/true density) *100.

The mass moisture was determined by the double weighing method. A composite soil sample was analyzed for pH, organic material, particle size distribution by the sieve method [1], mineral nitrogen by the Kjeldahl procedure after acid digestion [2], available Phosphorus by Spectrophotometry [3], and exchangeable Potassium by flame photometry [4].

The Mint methanolic extracts were analyzed for their extraction yield of phenolic compounds, their chemical characterizations by the determination of total phenols [5] and flavonoids [6] and their antioxidant activity by the DPPH test [7].

The statistical results of soil analyzes were carried out by the Minitab statistical software and the graphic outputs of two analyzes (Soil + Methanolic extracts) were carried out with Excel 2007 software.

3 Results and Discussions

3.1 Soil Test Results

3.1.1 Mass Moisture (%)

Over time, the results showed that the addition of biochar (B) or compost (C) separately or in combination (C + B) improved the mass moisture remarkably compared to the control (T) (Fig. 1). This can be explained by the fact that compost delivers more or less stabilized organic matter to the soil which positively influences water regulation [8] and on the other hand the porous structure of biochar which allows the retention of water [9].

Also the water can be retained by capillary forces related to the porosity of biochar, which promotes fluid retention.

Biochar influences the dynamics of water in soil. Thus, its microporosity promotes an increase in water retention, because it increases capillary rise and its macroporosity increases soil drainage when it is very wet and therefore its aeration [10]. The high porosity in biochar significantly improves the water retention capacity of the soil [11] and among others its moisture humidity.

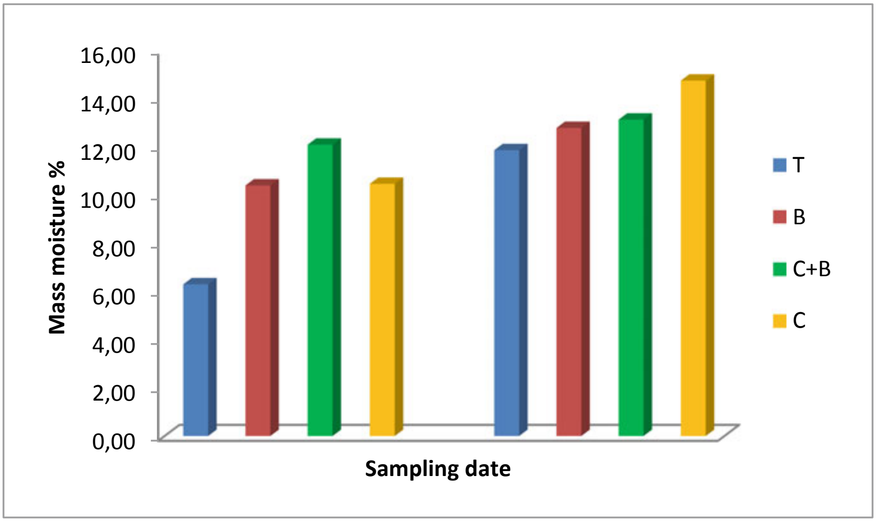

Fig. 1 Evolution of the mass moisture of the soil according to the treatments over time (Ouertatani. 2016)

This study also showed that the best water content was obtained with compost applied alone. Contrary to these results, [12] have shown that applying biochar + compost has a more positive effect on water availability than compost alone.

3.1.2 Porosity Index (% Ip)

The biochar treatment gives the best porosity index in comparison with the control, unlike that of the compost, which gives the low porosity index at the first sampling. The best result obtained by the biochar in the first date can be justified by the fact that it consists of macro and micropores [9].

For the 2nd sample, the porosity index increases regardless of the type of treatment with the best result obtained with the control treatment (Fig. 2). Thus, the highest porosity index obtained for the control and which is insignificant ($P > 0.05$) can be explained by the incorporation of manure before the installation of culture.

3.1.3 Structural Stability

During the first sampling, the combination (compost + biochar) improved very significantly ($P = 0.001$) this parameter compared to the control. However, compost gives low value compared to other treatments (Fig. 3).

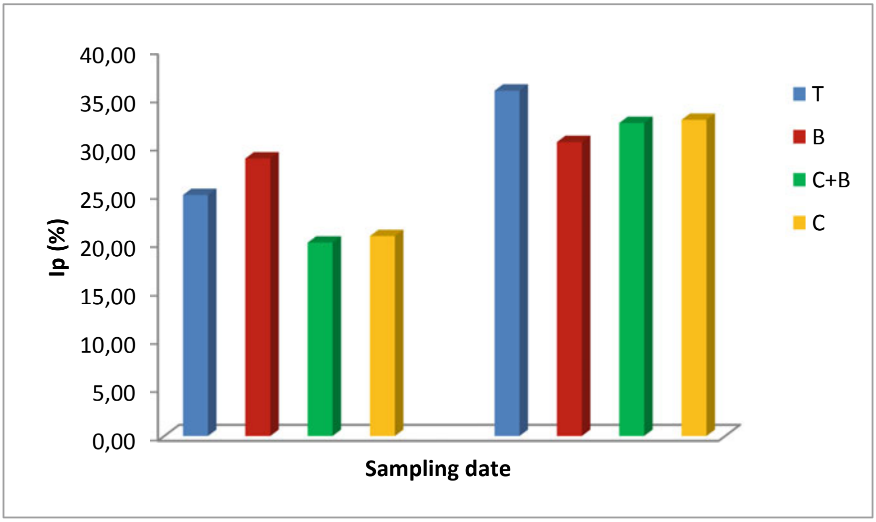

Fig. 2 Evolution of soil porosity according to the treatments over time (Ouertatani. 2016)

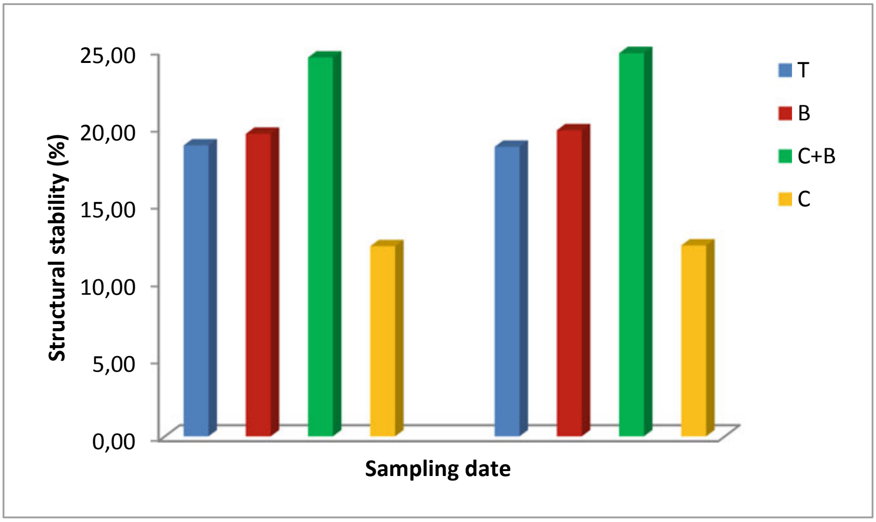

Fig. 3 Evolution of the structural stability of the soil according to the treatments over time (Ouertatani. 2016)

In the second date, there was a slight non-significant increase ($P > 0.05$) of this parameter in descending order: compost + biochar, followed by biochar, later the control and finally compost.

These results can be interpreted by the fact that the biochar improves the stability of the micro-aggregates and thus the improvement of the structural stability of the soil which is in agreement with Brodowski *et al.* [13]. Thus, the increase in organic matter, microbial biomass and its activity is accompanied by the formation of larger and more stable aggregates [14].

3.1.4 Mineral Nitrogen (N)

The figure below indicates that for both sampling dates the biochar and compost used separately or combined increased very significantly ($P > 0.001$) the soil mineral nitrogen content.

At first sampling, the combination (compost + biochar) has the highest nitrogen content compared to the control, followed by biochar and compost applied separately.

Regarding the second date, the nitrogen levels of different treatments increase following the same order of the first sample except that of the control which lowered slightly because of the nutritional needs of mint.

Indeed, these results are justified by the fact that the biochar increases the cation exchange capacity and among other things the nitrogen content. Research has shown that the application of soil biochar can improve the cation exchange capacity of soils from which a reduction in nutrient leaching results. The alkaline nature of biochar improves the availability of soil nutrients [15–17].

However, these results are contradictory to those of Lehmann and Joseph [17] who proved that the addition of biochar inducing an increase in biomass and microbial growth can reduce the availability of nitrogen in the soil by its immobilization by the soil microorganisms (Fig. 4).

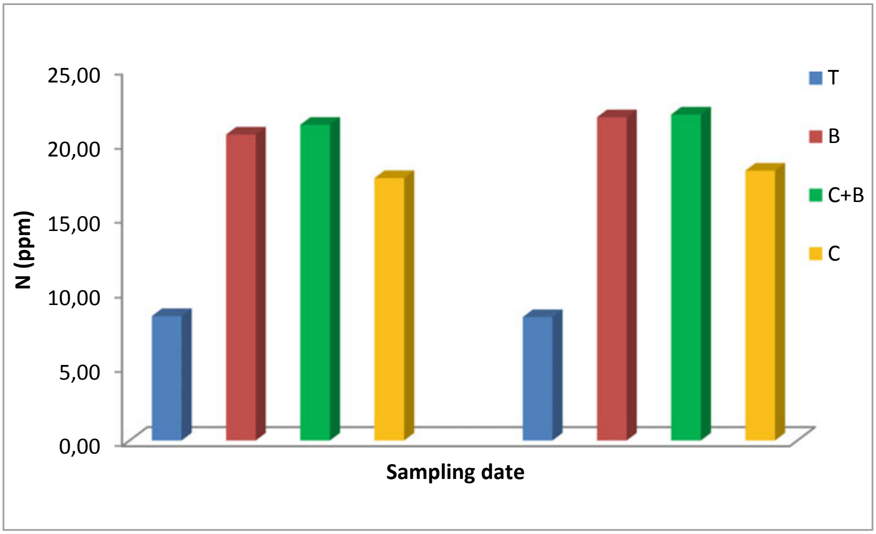

Fig. 4 Evolution of the soil mineral nitrogen content according to the treatments over time (Ouertatani. 2016)

3.1.5 Available Phosphorus (P)

The figure below shows that for the first sample, the compost + biochar mixture improved the phosphorus content especially ($P < 0.001$) compared to the control, followed by biochar and compost. In the 2nd sample, the phosphorus contents continue to increase but in a non significant way compared to the contents obtained at the first sampling. This increase in the P content due to these organic treatments is due to the fact that these organic compounds are sufficiently rich in P. The study by Egamberdieva *et al.* [18] showed that the concentration of P increased by 75%, that of in soils amended with biochar.

Laurin-Lanctôt's research [19] has also confirmed that the amount of P in the soil reserve has been greater in substrates modified with biochar (Fig. 5).

3.1.6 Exchangeable Potassium (K)

Separately applied biochar or compost increased the soil content in K very significantly ($P > 0.001$). These significant variations returned to the high K biochar content (1 to 58 $g.kg^{-1}$). [20] and the stable organic matter forming the compost which gives it a capacity to retain the cations against leaching [21]. These results confirm those of Egamberdieva and *al.* [18] which have shown that the concentration of K in root tissue and plant shoots was increased by amendment with biochar.

The biochar is able to retain nutrients in the soil and promote their mineralization thus increasing the availability of nutrients to the plant, including potassium [17].

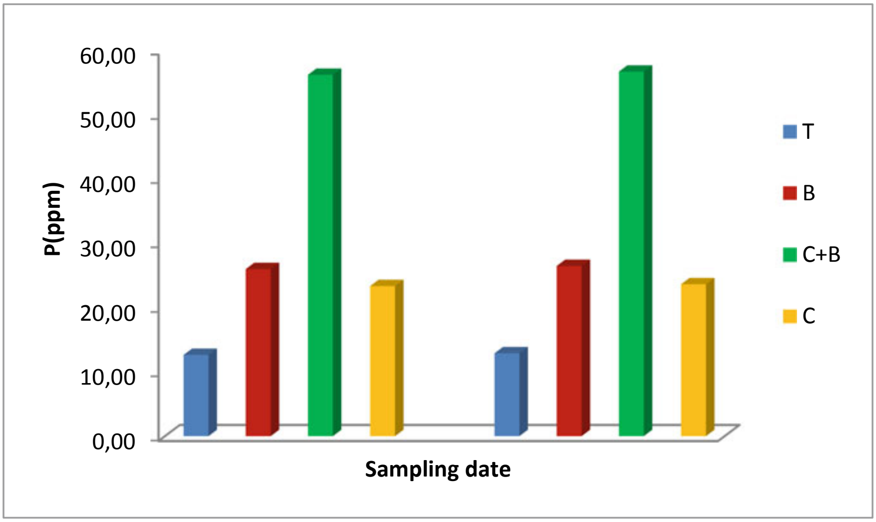

Fig. 5 Evolution of the soil content of available phosphorus according to the treatments over time (Ouertatani. 2016)

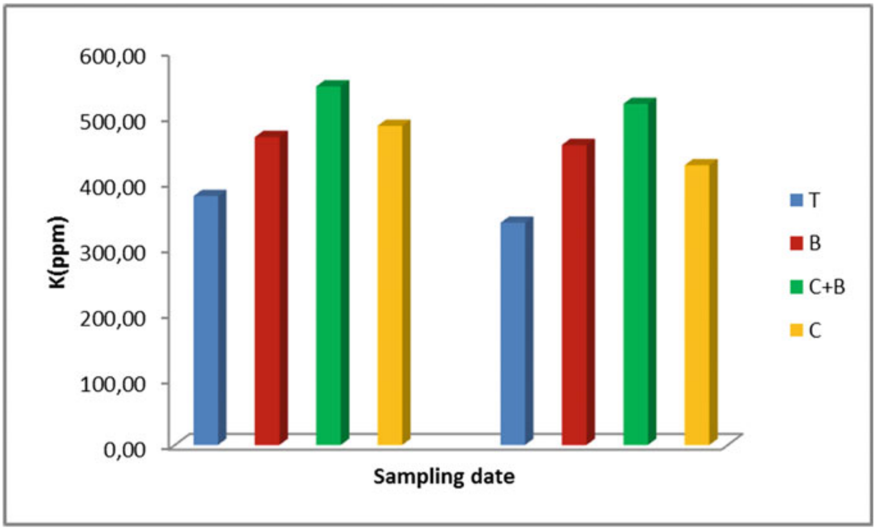

Fig. 6 Evolution of the soil content of exchangeable potassium according to the treatments over time (Ouertatani. 2016)

The combination (compost + biochar) gives the best potassium content in comparison with the control at the 1st sample and the second sample with a slight non-significant decrease ($P > 0.05$) obtained with all treatments over time that is due at the absorption of this element by the plant of the mint (Fig. 6).

3.1.7 Organic Matter

The following figure shows that the combination in the first sample yields the highest organic matter content compared to the control followed by compost and finally biochar. This highly significant increase ($P > 0.001$) of OM content is justified by the delivery of organic carbon by compost and biochar. This is due to the ability of biochar to increase the efficiency of carbon use by soil microorganisms. Thus it decreases the amount of CO_2 in the air and increases the amount of C in the soil [22]. For the 2nd sample, these levels continue to increase non-significantly ($P > 0.05$) as a function of time (Fig. 7).

These results were proven by a two-year study by Lentz and Ippolito [23] who found that total organic carbon increases significantly with a biochar amendment compared to the unamended witness.

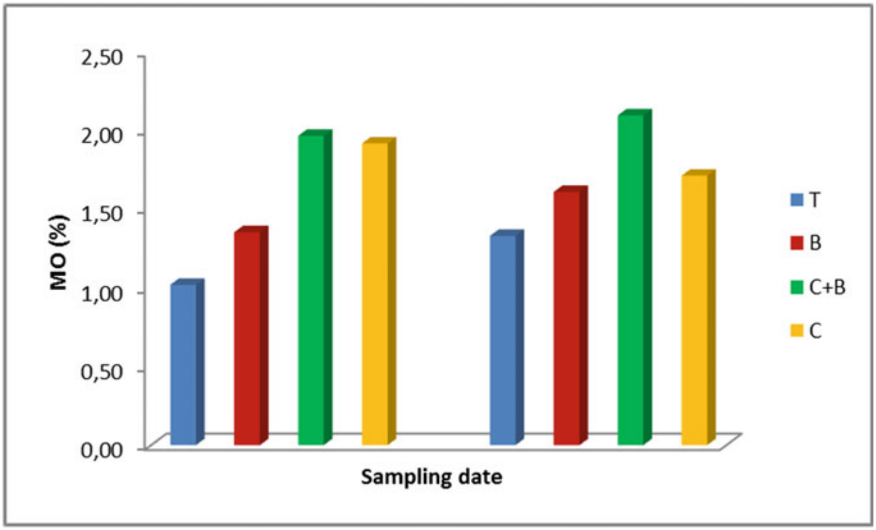

Fig. 7 Evolution of the soil content in organic matter according to the treatments over time (Ouertatani. 2016)

3.1.8 Soil pH

From Fig. 8, it is noted that at first sampling, only the biochar significantly increased ($P < 0.05$) the pH of the soil compared to the unamended control. On the other hand compost alone or combined with biochar significantly decreased the pH because of the organic acids released into the soil during the decomposition of the MO contained in the compost.

However, composts are generally prepared from manure droppings known for their acidifying properties may have caused the lowering of soil pH. A decrease in pH is evoked by some studies after application of organic amendments of animal origin on soils with a neutral to basic pH [24].

On the other hand, the biochar may contain varying concentrations of alkaline ash that could be easily released and leached into the soil and attenuate its acidity [25]. Thus, the effect of biochar on the soil pH is conditioned by the content and nature of the ash, in direct relation with the raw material and the production process used.

In the second sample, the pH of the elementary plots decreases not significantly ($P > 0.05$) regardless of the type of treatment, but the biochar still has the highest pH value.

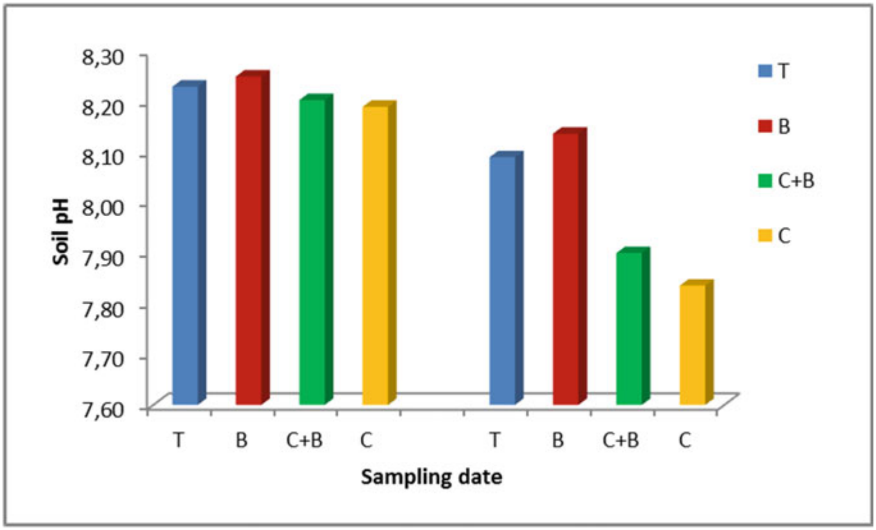

Fig. 8 Evolution of soil pH according to the treatments over time (Ouertatani. 2016)

3.2 *Chemical Characterization and Evaluation of the Antioxidant Potency of Methanolic Extracts of Mint*

In this part, we will first present the results of extraction yields and those of the chemical characterization of the methanolic extracts obtained by the determination of total phenols and flavonoids.

Second, we will evaluate their antioxidant activity.

3.2.1 Extraction Yield

The yields of methanolic extracts (EM) mint were determined relative to the mass of the plant material extracted. The results obtained (Fig. 9) show that the EM yields obtained from mint leaves fertilized with biochar (R = 31.34%) and EM of the control test (R = 30.1%) are comparable.. However, we note that these are higher than those obtained from mint leaves fertilized with compost (R = 22.24%) and with the biochar-compost mixture (R = 20.72%).

These results clearly indicate the richness of mint leaves fertilized with biochar compared to the other studied parts of the plant.

These results are superior to those obtained for the methanolic extract of Brazilian mint (R = 5.96%) [26].

Moreover, the extraction yield is not influenced by certain extraction factors: residence time, temperature and the solvent-vegetable matter ratio extracted [27].

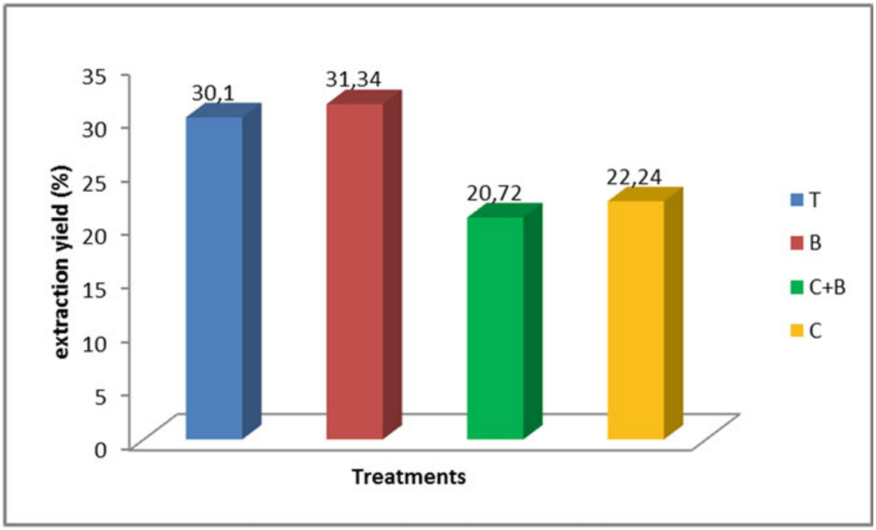

Fig. 9 Extraction yield of mint leaves according to treatments (Ouertatani. 2016)

3.2.2 Chemical Characterization Of Methanolic Extracts

In this part, we are interested in the spectrometric quantification of the phenolic composition of methanolic extracts.

Determination of total phenols

The total phenol concentrations in the methanolic extracts of the mint leaves: control EM, EM biochar, EM compost + biochar and EM compost are, respectively, of the order of 52.74 ± 3.3 mg eq AG/g of mint dry; 71.48 ± 5.90 mg eq AG/g dry mint 17.98 ± 0.30 mg eq AG/g dry mint and 48.3 ± 0.04 mg eq AG/g dry mint (Fig. 10).

These results show that spearmint leaves are very rich in phenolic compounds. Phenolic compounds correspond to bioactive molecules extracted from plants that are generally known by their powerful power to reduce free radicals and stabilized them, prevent the oxidation of cell molecules and inhibit the germination of pathogenic bacteria [28, 29].

According to Fig. 10, the extract obtained from mint fertilized with biochar contains the highest total phenol content (71.48 ± 5.90 mg eq AG/g dry mint). This result is explained by the fact that biochar contains multiple organic compounds such as phenols [30].

On the other hand, EM compost + biochar showed the lowest total phenol content. This low content may be related to fertilization with the biochar and compost mixture, which may have an antagonistic effect on the total polyphenol content. From which it can be suggested that the nature and composition of the soil can influence the content of phenolic compounds. Work done on the vines has shown that water stress

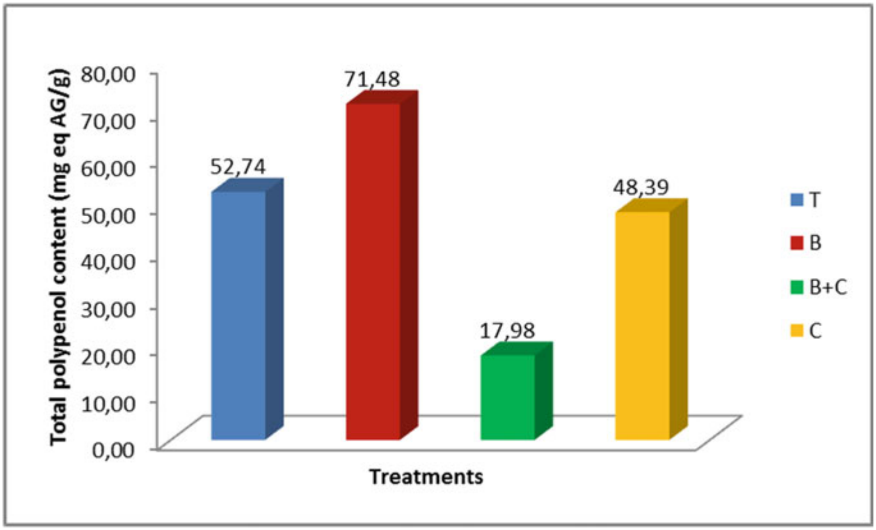

Fig. 10 Total polyphenol content of the methanolic extracts according to the treatments. (Ouertatani. 2016)

reduces photosynthesis, promotes stunting, limits the size of berries and stimulates the synthesis of phenolic compounds [31, 32].

<u>Determination of flavonoids</u>

Figure 11 illustrates the content of flavonoids present in the four methanolic extracts studied. It shows that mint leaf extract fertilized with biochar is the richest extract of flavonoids (56.00 ± 11.89 mg eq Quercetin/g of dry mint), followed by unfertilized mint (48.79 ± 13.37 mg eq Quercetin/g dry mint), mint fertilized with compost (45.66 ± 1.14 mg eq Quercetin/g dry mint) and mint fertilized with the mixture (biochar + compost) (37.63 ± 3.92 mg eq Quercetin/g of dry mint). This can be explained by the same causes cited for total phenols.

These results are significantly superior to those found by Brahmi and *al.* [33].revealed for ethanolic extracts of various defatted mint species: M. spicata (2.45 ± 0.02 mg eq Quercetin / g dry mint), M. pulegium (0.85 ± 0.01 mg eq Quercetin / g dry mint) and M. rotundifolia (3.30 ± 0.10 mg eq Quercetin/g dry mint).

Flavonoids is the most representative group of phenolic compounds. These molecules have various chemical structures and their own characteristics. They can participate in photosynthetic processes in gene regulation and in growth metabolism [34]. They possess many therapeutic virtues. They are particularly active in maintaining good circulation. Some also have anti-inflammatory and anti-viral properties, others have protective effects on the liver [35].

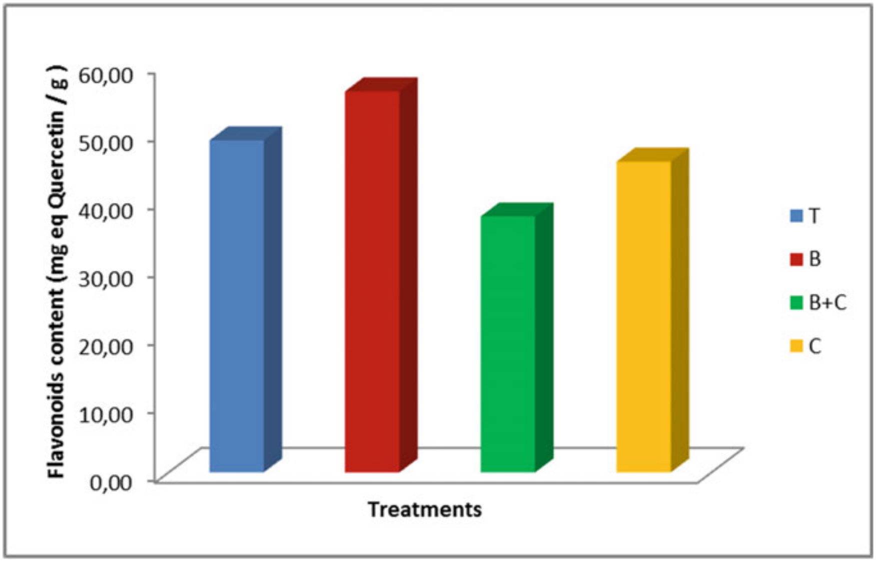

Fig. 11 Flavonoids content of methanolic extracts according to treatments (Ouertatani. 2016)

3.2.3 Study Of The Antioxidant Power

In this part, the corresponding methanolic extracts were subjected to an evaluation of their antioxidant activity by two methods, namely the DPPH test and the FRAP test.

Anti-radical activity on the free radical DPPH
In order to evaluate the antioxidant power of methanolic extracts obtained from mint subjected to different types of fertilizer, the percentage inhibition (PI%) of the oxidative effect of DPPH. has been determined. The values obtained made it possible to represent the percentage inhibition as a function of the concentration of the samples (Fig. 12).

Figure 12 shows the percentages of inhibitions (PI%) of DPPH. increase proportionally with the concentration of the methanolic extracts studied. At the maximum concentration of 1 mg/ml of control methanolic extract, EM biochar, EM compost + biochar and EM compost, the antiradical activity expressed as percentage inhibition is, respectively, of the order of 72.29; 87.58; 72.89 and 83.05%.

These results show the richness of the various methanolic extracts studied in free radical scavenging molecules essentially for EM biochar and EM compost extracts.

This increase in the percentage of inhibition can be explained by the composition of the methanolic extracts which is rich in antioxidant molecules. This composition varies according to the nature of each extract.

The antiradical activity is generally expressed as a function of the effective concentration EC_{50} (Fig. 13) which corresponds to the concentration necessary for the

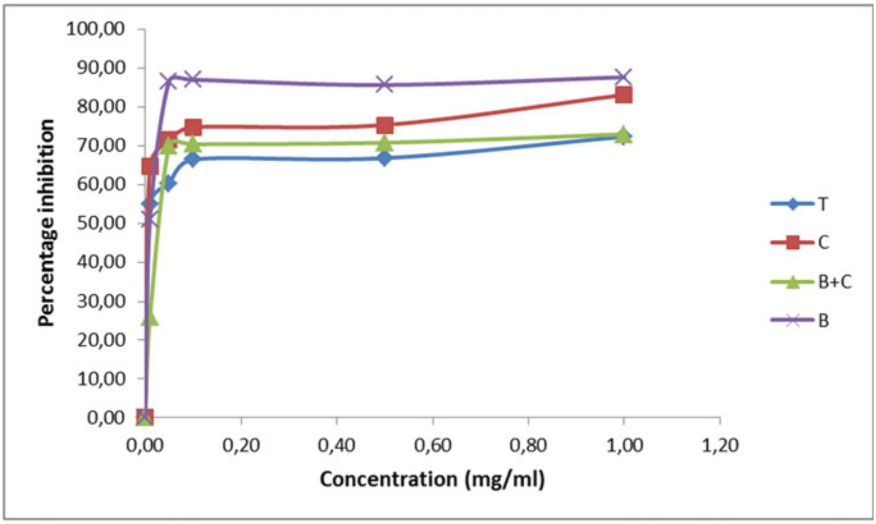

Fig. 12 Percentage inhibition of DPPH depending on the concentrations of different methanolic extracts of mint (Ouertatani. 2016)

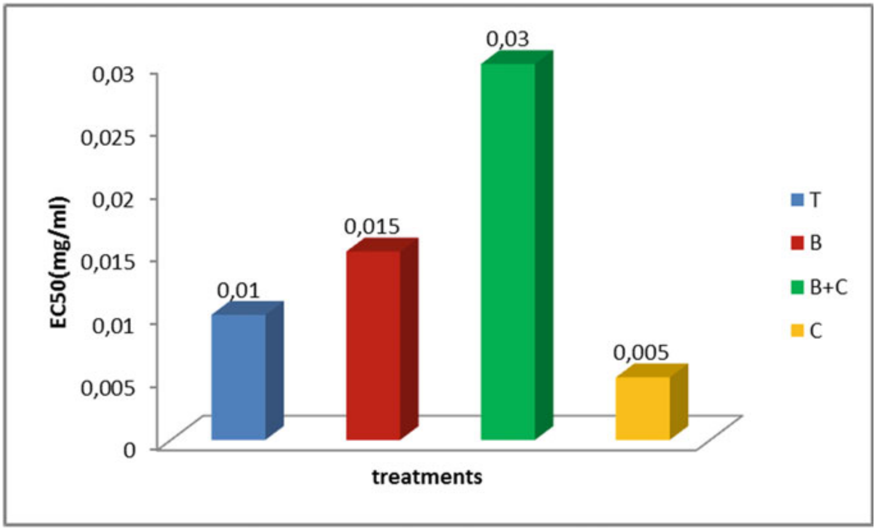

Fig. 13 Effective concentrations (EC_{50}) of the different methanol extracts of mint (Ouertatani. 2016)

antioxidant to inhibit 50% of the initial concentration of the free radical. It is estimated that plus EC_{50} is low the more anti-radical activity is high.

We note that the EM compost has the lowest EC_{50} value of the order of 0.005 mg/ml, followed by the control EM ($EC_{50} = 0.01$ mg/ml), then the EM biochar ($EC_{50} = 0.015$ mg/ml) and finally EM compost + biochar ($EC_{50} = 0.03$ mg/ml). This suggests a better antiradical activity of EM compost compared to other extracts.

Test du pouvoir réducteur (FRAP)

L'activité antioxydante des extraits méthanoliques de la menthe est aussi évaluée par le test de la réduction du fer (FRAP). La présence des réducteurs dans les extraits provoque la réduction de complexe ferricyanide Fe^{3+}à la forme ferreux Fe^{2+}. Therefore, Fe^{2+} can be evaluated by measuring and monitoring the increase in color density in the reaction medium at 700 nm.

The results of the variation of the optical density as a function of the concentrations of the methanolic extracts are illustrated in the Figs. 14 and 15.

Figure 15 shows that the optical densities increase proportionally with the concentration of the methanolic extracts studied. At the maximum concentration of 1 mg/ml, the optical density measured at 700 nm has values of 1.93 for control EM; 1.84 for EM compost; 1.82 for EM compost + biochar and 1.93 for EM biochar. The reducing power of an antioxidant can be characterized by a quantity called the effective concentration $EC_{0.5}$ (Fig. 15) at which the absorbance of the mixture measured at 700 nm

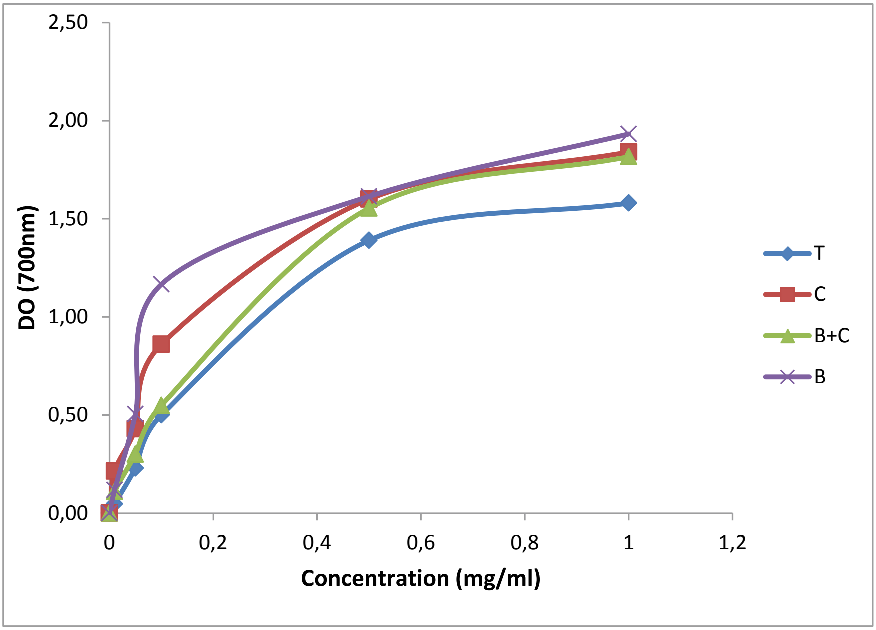

Fig. 14 Optical density as a function of the concentration of methanolic extracts: Effect of the extracts on the reducing power of iron. (Ouertatani. 2016)

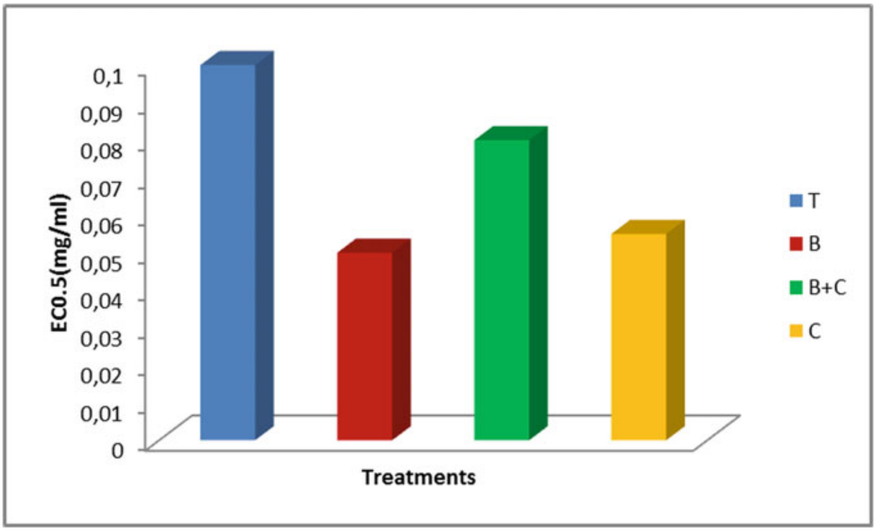

Fig. 15 Effective concentrations ($EC_{0.5}$) of different types of methanolic extracts (Ouertatani. 2016)

is equal to 0.5.It is estimated that plus $CE_{0.5}$ is low plus the antioxidant activity is high.

According to this figure, it is noted that EM biochar has the best iron reducing activity with a CE0.5 of 0.05 mg/ml followed by EM compost which has a CE0.5 of 0.055 mg/ml. then the EM compost + biochar with a CE0.5 of 0.08 mg/ml and finally the control EM having a CE0.5 of 0.1 mg/ml.

Based on the previous results of the evaluation of the antioxidant activity of the methanolic extracts of the four mint samples, we find that the mint fertilized with the biochar and the compost manifests the antiradical activity (EC 50 = 0.015 mg/ml and 0.005 mg/ml, respectively) and the iron reducing power (EC0.5 = 0.05 mg/ml for both extracts) highest. These samples have the highest levels of total polyphenols (71.48 and 52.74 mg eq AG/g, respectively) and total flavonoids (56.00 and 45.66 mg eq Quercetin/g, respectively).

4 Conclusion

This work was carried out in order to evaluate the effects of organic fertilization (biochar and compost) on the physico-chemical parameters of the soil and on the chemical composition and quality of extracts of sweet mint (Mentha spicata).

For the soil parameters (N, P and K content, MO, porosity, moisture…), the difference was observed between the types of fertilization is remarkable. Indeed soil analysis has shown that the blocks fertilized by Biochar + compost are the richest in mineral nitrogen, potassium and phosphorus and organic matter.

A second part is performed for Mentha spicata to determine the chemical composition of its methanolic extracts and the biological activities of its oil and extracts.

The yield of methanolic extract differs according to the type of fertilization. Concerning the polyphenol and flavonoid contents, the organic fertilization has a more pronounced effect compared to the control. The highest polyphenol and flavonoid content is recorded for biochar applied alone.

The evaluation of the antioxidant activity of the methanolic extracts by the DPPH and FRAP methods has shown that the methanolic extracts of Mentha spicata are characterized by a very interesting antioxidant activity. Our study gave good results for inhibition of bacterial growth by methanolic extracts of Mentha spicata.

Subsequently, we can conclude that organic fertilization can be a solution to improve the quality of aromatic and medicinal plants and the quality of methanolic extract and at the same time serves to reduce the impact of chemical fertilization.

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Sustainable Agriculture Water Management

Assessing the Water Productivity of Durum Wheat in Tunisian Semi-Arid Conditions

Sami Bhouri Khila, Boutheina Douh, Amel Mguidiche, and Abdelhamid Boujelben

Abstract In semi-arid Mediterranean countries where crop yield is primarily water-limited, the topic of increasing productivity and water use efficiency is of great concern. The focus on water productivity of main crops is an imperative imposed by the critical situation of water resources as well as an ever-growing demand. However, there are still some gaps with respect to crop water use efficiency and productivity. The scope of this report is to establish the state of knowledge on water use efficiency and to help identify the possible margins of progress in terms of water productivity of wheat conducted in rainfed and irrigated conditions. Moreover, the inter relationship between crop yield, water use and water use efficiency were determined for Durum Wheat grown in Tunisian semi-arid conditions. The relationships have important implications for achieving efficient use of water resources in water-scarce areas. The methodology was mainly based on long-term simulations using the STICS crop model. The simulations were performed assuming a long-term weather database and representative soil types of the study area, chosen on the basis of their available soil water in the root zone. The analysis suggested that, under limited water resource conditions, full supplemental irrigation should be replaced with a level of deficit irrigation that should maximize water use efficiency.

Keywords Water use efficiency · Yield · Durum wheat · Crop model

1 Introduction

In semi-arid Mediterranean countries, while food production must increase to feed an ever-growing population, the amount of irrigation water available is declining [1]. Agriculture, as the main consumer of freshwater, is currently faced with the

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challenge of a new approach to water resource management that insures the protection of water resources and their integrity [2]. Thus, it is important to adopt water management strategies to produce "more crop per drop", by increasing agricultural water productivity [3, 4].This is particularly the case of wheat, which is a major diet component in the Mediterranean countries [5, 6]. The wheat-growing area within the Mediterranean Basin represents 27% of the arable land and the region represents 60% of the world's growing area for durum wheat [7]. Maximizing water use efficiency (WUE) will be essential in areas where water is the most limiting factor for wheat production [8]. Proper Irrigation water management is a key factor to increase water use efficiency [9–11] particularly in Mediterranean climatic conditions [12]. Indeed, for optimal irrigation scheduling, crop water use efficiency of Durum Wheat may be 44% higher that obtained under rainfed conditions [13, 14]. Optimal irrigation management practices imply appropriate knowledge of crop water use and responses to water deficits [1].

Moreover, when providing operational suggestions to optimize on-farm water management, the relationships between crop production and water use should attentively be considered. In effect, they are essential for effective allocation of water resources and for improving WUE [15]. Crop yield- Water relations allows to quantify the effects of water management on crop productivity [16] and to optimize irrigation scheduling [16].Thus, they can provide a certain amount of settlements [15] particularly in the arid and semi-arid regions [15]. The present study deals with water productivity of durum grown under semi-arid conditions. Relationships of grain yield, water use and water use efficiency were developed for wheat grown under semiarid Mediterranean conditions using the STICS crop model. The established relationships were used to estimate the levels of irrigation for efficient management of water resources for wheat production.

2 Agricultural Water Use Efficiency in Tunisia

2.1 Water Use Efficiency and Productivity Concepts

Definitions of water use efficiency depend on the considered perspective. Typically, water efficiency is used as an indicator to account for water losses occurring during its use [16]. Thus, water network efficiency is defined as the ratio between the volume of water delivered to the farms and that delivered by the conveyance system [17]. Application efficiency accounts for water losses by deep percolation and by runoff during irrigation [18]. It is defined as the ratio between the volume of water stored in the root zone and that applied during irrigation [18, 19]. Storage efficiency is defined as the ratio between water stored in the root zone and the maximum soil storage capacity [18]. Moreover, water use efficiency and productivity terms may also be defined to assess the efficiency of the processes in which water is used to produce new entities [19]. In this case, the WUE terms are presented as Crop water use efficiency or water productivity. Different definitions have been proposed and discussed [2]. Generally, crop water use efficiency may be determined according to two approaches. The ecophysiological approach is based on the analysis of the relationship between photosynthesis and transpiration per leaf unit area [20]. Whereas the agronomical approach is based on water consumption and yield concept. In this case, crop water use efficiency is defined as the ratio between crop yield and water consumption [21]. It is an indicator of the efficiency of the process by which the water is consumed by the plant to produce the biomass [22]. Yield can be indicated by global dry matter or marketable crop yield. While water consumption may be assimilated to crop evapotranspiration, rainfall and irrigation amount to define respectively crop water use efficiency, rainfall use efficiency and irrigation use efficiency [8, 23, 24]. The variability in determining crop WUE can be attributed to agro-techniques, plant characteristics and environmental conditions [2]. However, the variability observed may be largely attributed to the water regime applied [25, 26].

2.2 Irrigation Water Use Efficiency

In Tunisia, as in most countries with arid and semi-arid climate, irrigated agriculture is the greatest consumer of water resources [27]. Even if the volumes allocated to irrigated agriculture will tend to decline, agriculture will remain by far the main water consumer beyond 2030 [28]. However, apart from the fact that irrigated agriculture consumes more water than other productive sectors, its management is far from optimal. Indeed, irrigation schedules applied by farmers are often inappropriate for local soil conditions and are not adapted to crop water requirements [28]. Farmers sometimes apply more irrigation water than is necessary to ensure maximum production and minimize the risk of falling yields. In this case, some of the water applied to the crop may be lost [29, 30]. A study by [31] in central Tunisia revealed that 31.7% of farmers delivered an irrigation amount exceeding the optimum. Moreover, irrigation at deficit doses is not well controlled by farmers [27]. This technique requires a good knowledge of the impact of a water deficit on plant growth in relation to crop cycle phases. Indeed, only 25% of Tunisian farmers use complementary irrigation in cereal crops management [32], although this is particularly recommended when water resources are limited [33]. Also, frequent losses in water supply and distribution systems [28, 34] result in low efficiency and an insufficient residual pressure for the use of modern irrigation techniques [34]. Thus, most farmers use gravity irrigation methods that result in limited efficiency [35]. Following the rehabilitation of collective water supply networks, reformulation of water pricing and the use of water-saving techniques at farm level [28], the overall efficiency of water network increased by 25%. Nevertheless, water saving efforts did not significantly alter water use efficiency at the plot scale [36]. Thus, crop water use efficiency is generally below expected values [31].

2.3 Water Use Efficiency of Wheat Under Semi-Arid Conditions

Under Tunisian conditions, water use efficiency by wheat increased over the last 50 years [37] following the emergence of new varieties characterized by faster development and growth and a more developed leaf area [38] as well as the improvement of cultural practices [39]. Tests conducted by [39] over a period of seven years in five Tunisian sites showed that water use efficiency of rainfed wheat ranges between 0.57 kg.m^{-3} in the semi-arid and 1.19 kg.m^{-3} in the sub humid. These values are in agreement with those indicated by [40] and [8] for experimental trials conducted under Mediterranean climatic conditions. In fact, under rainfed conditions, crop water use efficiency of durum wheat is estimated at 0.76 kg.m^{-3} in average for Mediterranean countries [13] while it is estimated for north African countries at 0.43 kg.m^{-3} on average [41]. However, WUE values of rainfed wheat remain relatively low due mainly to irregular and insufficient rainfall [42]. Low values are also due to water losses by runoff and deep percolation in soils with limited water storage capacity located in semi-arid areas [43]. The crop suffers from water stress conditions during drought periods, resultingin stomata closure, reduced photosynthesis [44] and rapid wilting of the plant [45]. However, [43] showed that it is possible to improve WUEc of rainfed wheat by improving rainfall water management. Indeed, rainfall water use efficiency could be improved up to 20%by establishing infrastructures for collecting rainwater lost by runoff [1]. The stored amount could be used in supplementary irrigation to supply the crop during drought periods [8]. Also,the study carried out by [25] showed that it is possible to improve WUEc of rainfed wheat by some agricultural practices. For example, it is possible to use fertilizers in early stages of crop development to allow early soil cover [46] and minimizes water loss through evaporation [47].This is particularly important in Mediterranean climatic conditions where evaporation can reach 75% of total crop evapotranspiration [48]. Under irrigated conditions, in Tunisia, several studies [39, 49, 50] have reported that crop water use efficiency of irrigated durum wheat varies between 0.99 and 1.66 kg.m^{-3}. These results are in agreement with those obtained by studies carried out in similar climates [51]. WUE of irrigated Durum wheat is generally below 1.48 kg.m^{-3} in semi-arid climates. Water use efficiency of irrigated wheat could be 44% higher compared to rainfed conditions [25] particularly in the Mediterranean climate [38]. Under irrigated conditions, the relatively high values of water use efficiency can be attributed to rapid leaf area development [46] as well as a well-developed root system for better extraction of water from the soil [50]. The rapid development of leaf area is a significant advantage in areas where soil evaporation is an important component of crop evapotranspiration [51]. It promotes the transpiration of the crop at the expense of the evaporation of soil water by reducing the radiation absorbed by the soil [51]. However, relatively low values of crop water use efficiency can be obtained following the application of high irrigation amounts of [52]. Typically, crop WUE increases with the increase in water consumption of the crop until reaching a threshold value from which efficiency tends to decrease [24].

3 Inter Relationship Between Yield, Water Use and Water Use Efficiency of Durum Wheat: A Case Study in Northeastern Tunisia

3.1 Study Area

The Oued Rmel irrigation scheme (35°55′ N–10°25′ E) is located in the Northeastern part of Tunisia (Fig. 1). The scheme, supplied by the OuedRmel dam, covers an irrigated area of about 4770 ha.

According to long term weather data (1986–2006) summarized in Table 1, maximum monthly temperatures range between 16 and 31ºC and minimum monthly temperature vary from 7 to 21ºC. Mean relative humidity varies from 65 to 74% and monthly rainfall ranges between 4 and 48 mm.

The irrigation season starts on mid October and ends on May 30th. The dominant crops are olive trees and cereals. Cereal crops are adapted to the characteristics of the water delivery and the climate of the area Bouficha [53]. durum wheat is sown generally between mid November and mid December. Durum wheat cultivar Karim (Triticum durum Desf. Var. Karim.) was considered to carry out the study as it is sown by most farmers in the study area and it represents 50% of the area sown to durum wheat in Tunisia [54].

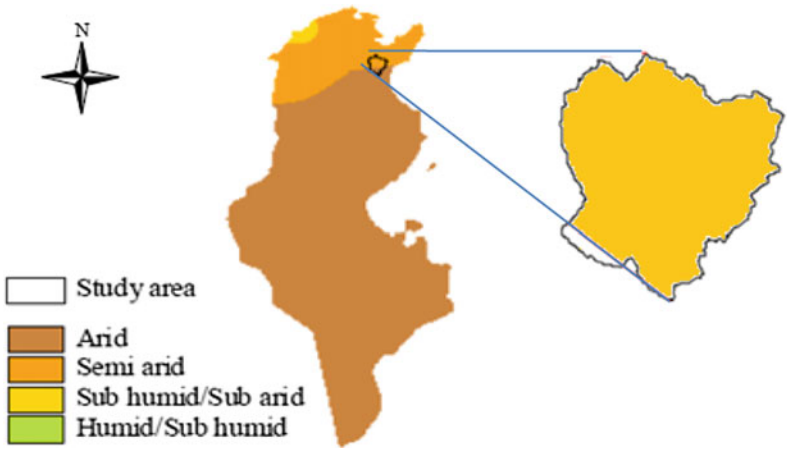

Fig. 1 Location of the study area

Table 1 Long term mean (1986–2006) meteorological data in the study area (source: National Meteorological Institute of Tunisia)

	Average of Température		Monthly total of precipitation (mm)	Mean relative humidity (%)	Wind speed ($m.s^{-1}$)
	T_{max}(°C)	T_{min}(°C)			
January	15.69	7.24	41.43	76.16	1.49
February	16.32	7.04	29.18	72.98	1.72
March	18.28	8.79	28.83	71.52	1.82
April	20.30	10.49	26.37	71.13	1.70
May	23.64	13.92	23.09	69.67	1.78
June	28.49	17.44	11.53	65.25	1.66
July	31.15	20.05	4.86	65.60	1.68
August	32.08	21.25	10.13	67.51	1.61
September	28.84	19.87	42.52	73.21	1.50
October	25.38	16.85	37.09	74.73	1.37
November	20.27	12.01	48.10	73.93	1.49
December	17.03	8.36	40.97	75.32	1.41

3.2 Methodology

The crop model STICS (Simulateur Multidisciplinaire des Cultures Standards) [55] was used to assess crop yield and WUE of durum wheat in the irrigated scheme of Bouficha as a function of irrigation regime, taking into account the pedoclimatic variability in the study area. The methodology applied in the model is described in Fig. 2. From the characterization of climate, soil, species and crop management, the model computes output variables related to yield in terms of quantity and quality, environment in terms of drainage and nitrate leaching, and to soil characteristics evolution under cropping system [56].

STICS model shows a wider scope, serving at the same time for research and management objectives [2]. The model was used to develop agronomic diagnosis [57], to improve crop management methods [58] and to study the effects of climate change on crop production [59]. STICS modeling principles are consistent with those originally stated by [60].

Daily accumulation of aboveground biomass is a function of photosynthesis, which consists of the conversion of intercepted solar radiation into biomass according to radiation use efficiency. Moreover, in order to test the level of accuracy of STICS in reproducing the actual system, Once the model was calibrated, model validation was carried out by comparing the simulated values of the output variables with those observed for a data set which was not used during calibration.

Moreover, the STICS model could be used to assess crop yield and WUE of durum wheat in Mediterranean conditions. Indeed, the results of model validation

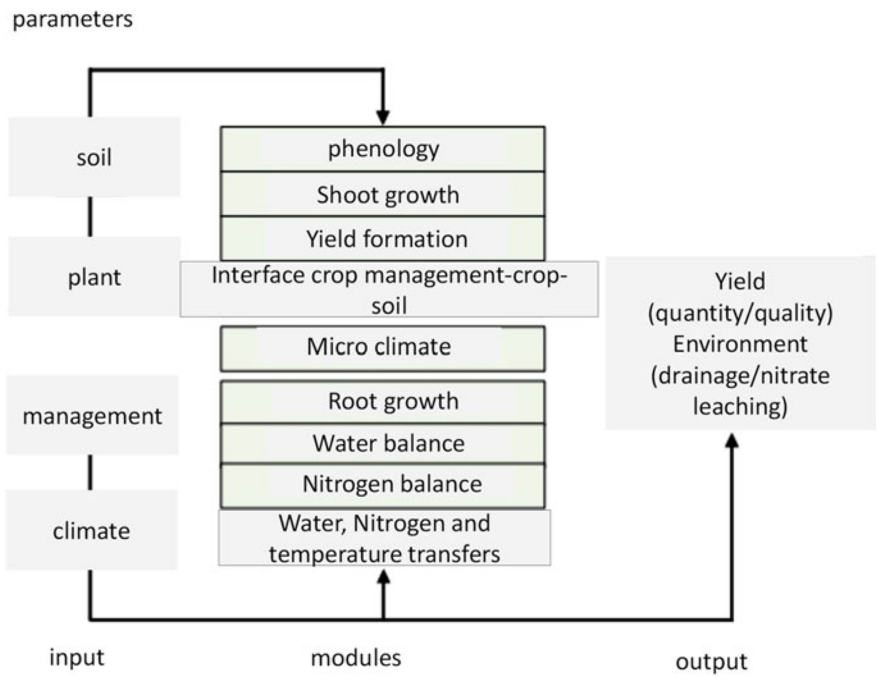

Fig. 2 Overview of the model system and its components (Heuer and Casper, 2011)

conducted by [61] showed the aptitude of the model in predicting crop yield and water consumption of Durum Wheat in a Mediterranean environment.

3.3 Scenarios of Irrigation Scheduling and Pedoclimatic Conditions

Following its calibration, STICS model was applied to simulate the effects of various irrigation scenarios on crop production and water consumption of durum wheat. Irrigation scheduling was simulated by STICS model based on an automatic option based on water depletion level. Thus, three scenarios of irrigation scheduling were designed: (i) irrigation was scheduled when 25% of the TAW was depleted (Irrigation scenario 1); (ii) irrigation was scheduled when 50% of the TAW was depleted (Irrigation scenario 2); (iii) Irrigation was scheduled when 75% of the TAW was depleted (Irrigation scenario 3). Simulations of above mentioned irrigation scenarios were carried out year by year assuming along term weather database (1986–2006 period) to take into account wet, average and dry years. Daily climate data on temperature, relative humidity, wind speed and radiation were documented using records from the nearby "OuedSouhil" weather station (latitude N 36° 27′, longitude E 10° 42′). While rainfall data was obtained from recorded measurements by a rain gauge situated on the irrigated scheme. In fact, on a regional scale, rainfall is much more variable than temperature or solar radiation [67]. According to local agricultural practices, the sowing took place every year, on November 15. At this date, the soil water reserve was supposed to be at field capacity. Fertilization is applied three times every year (sowing, tillering and heading) at a rate of 100 kg ha^{-1} of N.

Moreover, simulations were performed assuming different soil types on the basis of their available soil water in the root zone (TAW). The TAW describes the available water storage in the soil, which may be exploited by the root system. It is defined as the difference between the soil water contents at field capacity (FC) and wilting point (WP), multiplied by the rooting depth [35]. As for durum wheat, [62] proved that the soil depth explored by the root system is not deeper than 1 m. The properties of the considered soils are presented in Tables 2, 3 and 4. According to [63], the considered soils show contrasting characteristics in terms of TAW. Simulations were performed assuming soils with poor TAW (lower than 100 mm), intermediate TAW(between 100 and 160 mm) and high TAW (higher than 160 mm). Soil characteristics were obtained from a pedological study elaborated by the *r*egional Agency for Agriculture Development of Sousse.

Table 2 Main characteristics of the soils with high TAW

Soil	Depth (cm)	Clay (%)	Limon (%)	Sand (%)	θ_{cc}(%)	θ_{pfp}(%)	Bulk density	TAW (mm)
S1	0–20	29	36	35	53	36	1.45	181
	20–40	41	36	23	53	36	1.45	
	40–70	48	39	13	57	37	1.5	
	70–100	44	50	5	45	27	1.4	
S2	0–20	24	12	65	38	19	1.4	188
	20–50	25	6	71	38	19	1.4	
	50–65	15	5	82	31	13	1.35	
	65–100	27	11	64	38	19	1.4	
S3	0–50	49	17	32	57	37	1.5	190
	50–80	48	17	32.5	57	37	1.5	
	80–100	11.5	84	3.5	31	14	1.35	

Table 3 Main characteristics of the soils with low TAW

Soil	Depth (cm)	Clay (%)	Limon (%)	Sand (%)	$\theta_{cc}(\%)$	$\theta_{pfp}(\%)$	Bulk density	TAW (mm)
S7	0–20	18	78	4	27	15	1.5	80
	20–50	13	83	4	11	4	1.35	
	50–100	11	83	6	11	4	1.35	
S8	0–50	16	80	4	11	4	1.35	55
	50–70	14	70	16	17	7	1.4	
	70–100	16	78	6	11	4	1.35	
S9	0–20	18	57	25	27	15	1.5	92
	20–60	10	65	25	17	7	1.4	
	60–100	11	85	4	11	4	1.35	

Table 4 Main characteristics of the soils with intermediate TAW

Soil	Depth (cm)	Clay (%)	Limon (%)	Sand (%)	$\theta_{cc}(\%)$	$\theta_{pfp}(\%)$	Bulk density	TAW (mm)
S4	0–40	15	5	82	29	15	1.5	155
	40–70	25	10	65	38	19	1.4	
	70–100	14	70	15	29	15	1.5	
S5	0–20	32	34	34	53	36	1.45	144
	20–60	44	15	41	53	36	1.45	
	60–100	15	13	70	29	15	1.5	
S6	0–30	15	70	14	29	15	1.5	140
	30–60	19	71	10	29	15	1.5	
	60–100	17	75	8	29	15	1.5	

Furthermore, two indexes have been proposed to analyse crop water use efficiency:

$$WUE_g = \frac{Y}{ET} \quad (7)$$

$$WUE_b = \frac{B}{ET} \quad (8)$$

Where.
WUE_b = crop water use efficiency at biomass basis ($kg.m^{-3}$).
WUE_g = crop water use efficiency at grain basis ($kg.m^{-3}$).
Y = grain yield ($kg.ha^{-1}$), B = dry matter at harvest ($kg.ha^{-1}$).
ET = seasonal evapotranspiration ($m^3.ha^{-1}$).

3.4 Inter Relationship Between Yield, Water Use and Water Use Efficiency

3.4.1 Yield Relation with Total Applied Water

The relationship between grain yield and the sum of precipitation (P) and irrigation amount (I) is presented in Fig. 3 using results from simulations of the above mentioned irrigation scenarios under various pedoclimatic conditions. The general aspect of the relationship is in agreement with the results obtained by [64] which showed that the variation of grain yield to total applied water is described using a quadratic equation. Results illustrated in Fig. 5 revealed that grain yield linearly increased with increasing water received by the crop during the growing season. It could be noticed that grain yield of 3t/ha is obtained when the total applied water reaches approximately 1500 m^3/ha.

Moreover, high water amounts are poorly valued by the crop. Indeed, results showed that yield decreased for water amounts exceeding 4500 m^3/ha. This is in agreement with the results obtained by [3] and [29] which showed that yield of durum wheat decreases for "very" high amounts of applied water. Such water amounts correspond to wet years characterized by intense precipitation regime [8, 65].

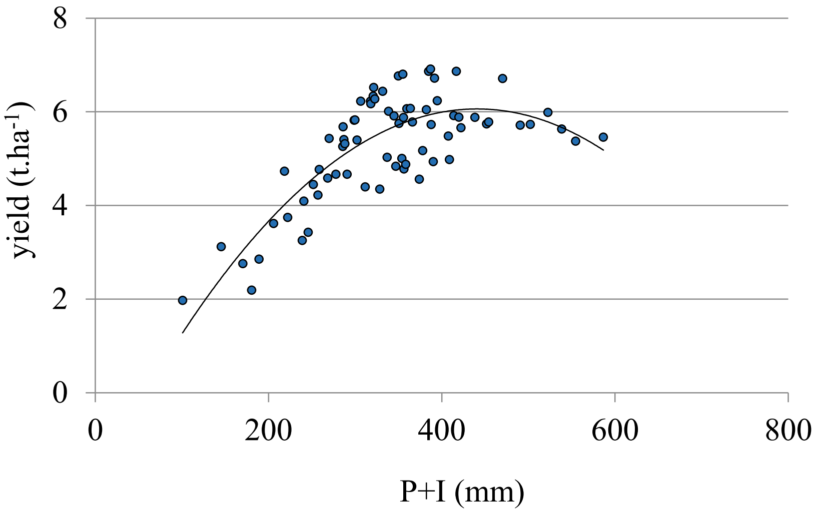

Fig. 3 Yield relation with total applied water

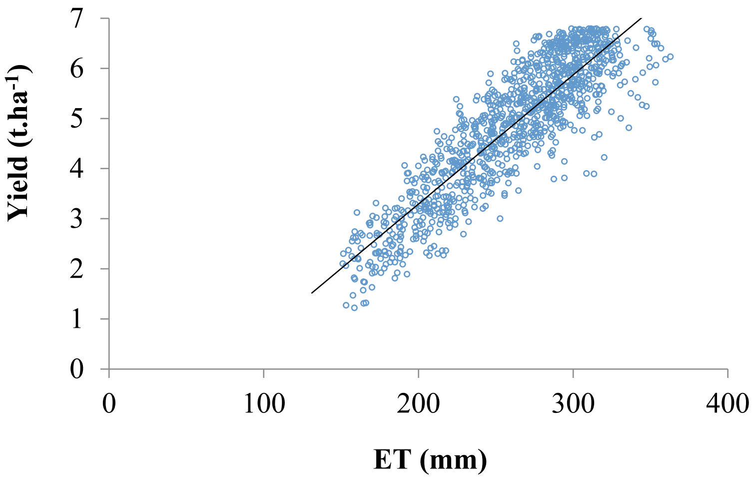

Fig. 4 Evapotranspiration-yield relationship

3.4.2 Evapotranspiration-Yield Relationship

The relationship between grain yield and crop evapotranspiration of wheat is illustrated in Fig. 4. It could be noticed that grain yield and evapotranspiration are linearly correlated. This result is consistent with those reported by several studies [9, 15, 66]. Seasonal ET ranged from 160 to 400 mm, and the corresponding grain yield ranged from 1.2 to 6.5 t ha^{-1}. The relationship indicates that for each 10 mm increase in ET, there was approximately a corresponding grain yield increase of 25.8 kg. The negative value of the intercept indicates that a certain seasonal evapotranspiration threshold value must be reached before any grain yield is obtained. This is in agreement with results obtained by [15]. However, the threshold value is larger than that obtained by [4] and [15] and lower than that indicated by [39]. Differences of ETC Threshold values can be attributed to differences in wheat variety and variability of climatic conditions [4].

3.4.3 Crop WUE –Water Consumption Relationship

Results showed that the relationship between WUE_b and evapotranspiration (Fig. 5) was related in a second order function. [67] and [24] established similar relationships for durum wheat.

The general trend was that, after an initial sharp increase, WUE_b reached its maximum at a given amount of ETC (about 350 mm) and decreased with any further increase in ETC. Adecline in grain yield per unit of water evapotranspirated is often associated with high values of ETC [68]. Such values are recorded at the stages of formation and grain filling.

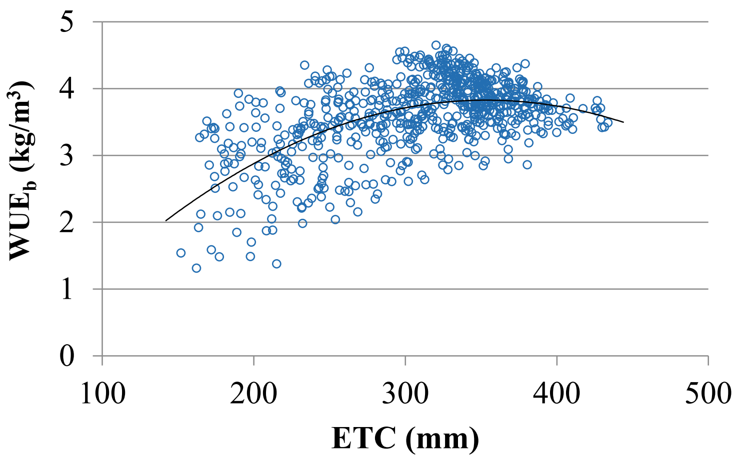

Fig. 5 WUE –ETC relationship

Moreover, the relationship between WUEg and water received by the crop from irrigation (I) and rainfall is illustrated in Fig. 5. The relationship can be described using a quadratic equation (Fig. 6).This is in agreement with the results obtained by [69] and [70].

Results revealed that WUE increased with increasing water amount received by the crop from irrigation and rainfall. However, when that amount was above 350 mm, WUEc gradually decreased. This is in agreement with the results reported by [52].

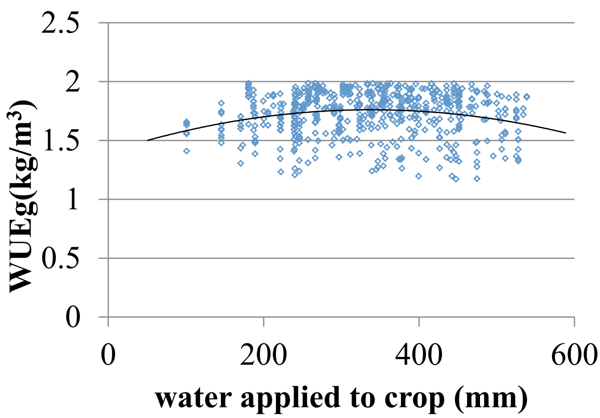

Fig. 6 Crop WUE –total applied water relationship

4 Discussions

Under irrigated conditions, the values of WUE are in agreement with those found by [71] and higher than those found by [39]. While under rainfed conditions, WUE values obtained are higher than the average value obtained in Mediterranean conditions [13]. Under irrigated conditions, the relatively high values of WUE could be attributed to reduced soil water evaporation due to a faster and more developed leaf area growth [51]. However, the statistical analysis did not reveal a significant effect of irrigation frequency on water use efficiency. This corroborates with the results reported by [24]. Nevertheless, as indicated by [72], WUE may decrease for high applied amount of water. Indeed, WUE tends to decrease if the amount of water received by the crop exceeds almost 3500 m^3/ha. In fact, high applied amount could provide favorable conditions for maximum crop evapotranspiration but may increase the losses by runoff and deep percolation. Moreover, as reported by [26], the water regime associated with maximum yield may not correspond to maximum water use efficiency. Thus, maximum WUE does not correspond to the highest yield values.

5 Conclusions

The present study focused on water use efficiency of durum wheat grown under semi arid Mediterranean conditions. Water-yield relations for Durum wheat grown under Mediterranean conditions were estimated using the STICS model. Results that irrigation makes it possible to increase water use efficiency of durum wheat. Indeed, grain yield increases with increased water received by the crop from irrigation and rainfall up to 4500 m^3/ha under Tunisian semi arid conditions. While WUE of Durum Wheat may decrease for water supply amounts exceeding 3500 m^3/ha.The curvilinear relationships of Yield and WUE with total applied water showed that high irrigation levels might not produce greater yield and water use efficiency. Thisemphasizeda policy for maximizing yield should be avoided under limited water resources conditions. Indeed, water regime corresponding to maximum WUE does not correspond to maximum grain yield.

6 Recommendations

Water productivity is becoming a key issue in Tunisia. Thus, future studies should focus on the assessment and analysis of water use efficiency of other strategic crops which are more sensitive to water stress. Moreover, research perspective is to study the combined effects of water regime together with fertilization regime on water use efficiency of durum wheat. Finally, given that climate is undoubtedly changing in Mediterranean countries, it could be interesting to investigate the impacts of the future climatic conditions on the crop yield-water relationships.

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Assessing Institutional Barriers to Effective Dissemination Strategies of Proven Water Management Practices to Face Climate Change Threats in the Citrus Growing Area in Tunisia

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Abstract Social and economic development depends on the sustainable management of natural resources to withstand shocks of climate change and reliably support livelihoods. In this context, extension and advisory services are critical for raising awareness and transferring knowledge to reduce farmers' vulnerabilities. This study critically examines the nexus between research, extension, and farmers focusing on institutionalized opportunities and barriers to transfer of knowledge on better water resource management in Cap Bon citrus area. Analysis of collected qualitative data reveals weak linkages between research and extension and the lack of accountability among relevant institutions. The study suggests that the extension delivery system can be greatly improved by abolishing administrative barriers, enhancing opportunities to transfer knowledge through improved communication and the feedback among the institutions, and granting extension agencies some autonomy.

Keywords Climate change · Agricultural extension · Institutional barriers · Tunisia

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1 Introduction

In the Mediterranean semi-arid context and under the pressure of increasing water demand from one side and the climate change from the other side, water resources are shrinking and critical thresholds of water availability and quality are threatening the sustainability of many agroecosystems. This is the case of the irrigated orange production area of the governorate of Nabeul of Tunisia, also known as the Cap Bon peninsula, where the prospect of increasing temperatures [1] and decreasing precipitations [2] are expected to exacerbate further water scarcity, exposing the sustainability of the production system to imminent risks and the community to serious social tensions among users. In this area, the adaptation capacity of the agroecosystem is limited by the lack of awareness about climate change challenges [3, 4], which is an important determinant of farmers and local stakeholders pro-environmental behaviours [5]. Indeed, despite the modernization efforts undertaken by the formal institutions to promote water saving and conserve quality resources, e.g., by subsidizing drip irrigation, on-farm water use was not significantly reduced [6], illicit wells number are increasing [7], surface irrigated areas are extending [8] and groundwater resources continue to be degraded [3, 9].

Given the scale of water resource problem in this region, and the economic importance of this production system at both local and national levels [10, 11], extension services are solicited to raise awareness and to disseminate the appropriate knowledge about new technologies for sustainable water management. The dissemination work is also a shared responsibility within institutions of research and the interfaces between extension and research. This institutional system is supposed to facilitate the transfer of information and strengthen the network of extension. However, increasing the rate of adoption, especially when some of these new technologies do not imply an immediate increase in the economic benefits to farmers, is difficult [4, 12, 13] and the continued low level of water productivity in irrigated areas and the current problematic situation are evidence of the slow uptake of new technologies by farmers and give the impression that the existing dissemination strategy has failed to mitigate the complex problem of water management effectively.

Many studies point to institutional barriers as a major cause of ineffective climate change adaptation [14–19] and the concern today is whether the current government extension system could achieve this explicit objective within current non-stable socio-economic environment after the civil uprisings of 2011 in Tunisia [20]. This study is, then, an attempt to understand the current institutional barriers to an effective dissemination of new irrigation technologies in the Citrus Cap Bon production area of Tunisia and the essential measures to be taken to overcome barriers with regard to the keys of better water resource management through surveying the involved institutions in the study area of Cap Bon.

2 Agricultural Extension System in Tunisia: An Overview

Technology diffusion in Tunisia is under the supervision of the government and the result of the interdependent multi-discipline institution efforts of research, extension and the interfaces between them. The private sector steps in rarely and acts especially to assist investors during the establishment of new agricultural exploitations. The extension system, was organized from the late 1980s and early 1990s in a hierarchical institutional way from Imada (community), Delegation and governorate to the central level of the Agricultural Ministry [21]. The well spread agricultural extension network over all the rural Tunisian territory made up by the Agricultural Radiance Centers (392 CRAs at the delegation level, [22]) and Extension Territorial Cells (185 CTVs at the delegation level, [22]) presents the basic extension institutions. These cells are governed by the Regional Agricultural Development Commissaries (CRDAs), through their Division of Extension and Promotion of Agricultural Production. There are 24 units of CRDAs, one in each Tunisian governorate. Private sector extension in Tunisia is regulated by law since 1998 and is represented by agricultural advisers who provide technical assistance in project and farm management. Currently, there are 179 firms accredited by the Ministry of Agriculture [23] but they have a limited potency in extension influence because Tunisian farmers with small and medium-sized farms make use rarely of the private service which is solicited by few big investors for the technical and economic feasibility of projects [24]. The Non-Governmental institutions are also not frequently involved in agricultural extension work.

The research institutions in Tunisia can have wide areas of action, e.g., the National Institute of Agricultural Research (INRAT) or specific domains, e.g., the National Institute of Agricultural Engineering Research, Forest and Water (INGREF) which is specialized in soil and water management and the Regional Center for Research in Horticulture and Conservation Farming (CRRHAB) which is specialized in conservation agricultural production system (Other important research institutions are forgotten. Remind the number of research institutions). To improve the links between research and extension, the works of the CRAs, CTVs and CRDA are supervised by two national coordinating institutions: The Agricultural Extension and Training Agency (AVFA) and the Institution of Agricultural Research and Higher Education (IRESA). Besides the agricultural extension activities, the AVFA provides the professional training in the areas of agriculture and fisheries and ensures the packaging of the research-validated results using printed technical documents and audio-visual materials with the objective of disseminating the awareness among farmers and other users in order to get them more involved in extension actions for the adoption of new technologies.

The Valorization and Innovation Directorate of the IRESA ensures the linking between extension services, agricultural research and higher education institutions. It is also in charge of gathering the research results and capitalizing on these to promote scientific and technical achievements. The validation of research results are performed by specialized technical centers such as the Technical Center of

Citrus (CTA) and The Technical Center of Organic Agriculture (CTAB). These interface institutions between research and extension experiment and study the technical–economic feasibility of the new technologies proposed by both the research and higher education institutions. They also perform the activities of training and monitoring in order to disseminate the appropriate knowledge.

3 Methodological Framework

Qualitative data was collected through key informant interviews held with heads of institutions that are directly or indirectly related to the agricultural extension system in the studied area (Table 1).

The interview questions covered a broad spectrum of subjects related to institutional mandates, organizational structures, and institutional role within the pluralistic extension system. Discussions on overall mandate included deliberations on the institutions goal and mission, targeted beneficiaries (e.g. small-scale farmers, large-scale farmers, etc.), sources of funding, intra-institutional linkages and partnerships,

Table 1 Institutions considered for the study

Type	Names	Number of interviewees
Regional Commissary	CRDA of Nabeul governorate	3
Extension institutions	CTV Grombalia, Soliman, Nabeul, BouArgoub, BeniKhalled, and MenzelBouzelfa. These serve nearly the entire Cap Bon citrus production area	9
Technical Centers	The Technical Center of Citrus (CTA) The Technical Center of Organic Agriculture (CTAB)	3
Interface institutions	IRESA and AVFA	3
Higher education	National Institute of Agronomy of Tunis (INAT) Higher Agronomic Institute of ChottMariem (ISA-ChottMariem)	2 2
Research Institutions	INRAT, INGREF, and CRRHAB	10
Professional organizations	The council of engineering association and UTAP	2
Water Distribution Associations	GDA, Two from MenzelBouzelfa, and one from BeniKhalled	3
Private Agriculture Advisors	Advisors working in Nabeul governorate	10

Source of the table: own elaboration 2018 as well as time allocated by field extension or advisory staff. Questions related to organizational structures included the legal status of the organization, its primary management authority, its organizational chart, and details about human resources—classified by gender and category and level of education. Inter-organization linkages among the various research and extension institutions were explored through questions that sought opinions on the importance, strengths, weaknesses, challenges, and opportunities for an effective agricultural extension system. All opinion and perception related questions were asked using a 5-point Likert-scale (e.g., very important, important, moderately important, slightly important, not important).

A second survey was also conducted among 147 farmers chosen in hazards to test the conceptual relationships between their perceptions about water management, extension institution, and proposed adaptation solution to climate change threats. This survey was presented in [4]. The response of farmers taken as binary in [4] are analysed from the original responses of farmers following a 5-point Likert-scale (e.g., strongly disagree, disagree, neutral, agree, strongly agree).

4 Results and Discussion

4.1 Barriers Related to Institution Organization, Human Resource and Decision Making

All the interviewed institutions, except the agricultural advisers, are under the supervision of the Ministry of Agriculture and share the same scarce financial government resources. Situated at the end of the hierarchical chain (Fig. 1), the extension system undergoes more this restrictive economic situation than the upper levels institutes, which limits the material means available to their institutions as cars, computers, internet connection, etc. The lack of resources slows down the spread of information flows about new technologies despite the well-dispersed geographical location of extension Tunisian network. In other words, the extension staff is out in the rural areas but does not have the resources to disseminate information. The financial barriers in the extension system were also emphasized in many countries by the review work of [14].

The process of administrative decision making of these institutions is mainly dependent on their head supervisors (president, director, or coordinator) in very hierarchical ways. Even at agronomic universities, research institutions and technical centers, which are managed by scientific and administrative councils, the final decision goes back to their directors, and the council views are consultative, not mandatory. However, the process of scientific decision making, especially in research and academic institutions, is somewhat anarchic because each researcher works without being effectively oriented, supervised and evaluated. Researcher teams frequently work unconnectedly without complementary efforts and the transfer of

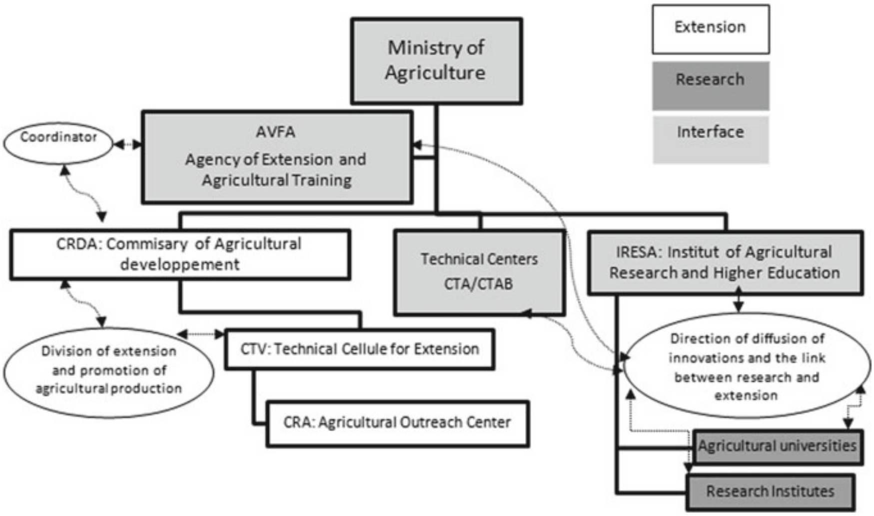

Fig. 1 Institutional linkages between the agricultural institutionsinvolved in the extension system. Continuous line represents the hierarchical relationship. Oval shapes represent the coordination units between the institutions

knowledge is unidirectional top-down from researchers to farmers through extensionists without any evaluation, participation, or feedback in the opposite direction. The divergent situation between administrative and scientific decision making processes and the lack of feedback between institutions at different levels of the knowledge transfer does not allow for identifying urgent research topics, gives rise to a confusing scientific environment, amplifies the redundancy of explored topics without wide cumulative novelties, and hinders the achievement of expected research project impacts.

In all the local level extension institutes (CTV and CRA), there are no clear terms of reference for staff positions including technical officers, field extension agents, and even sometimes administrative staff. Overlapping of roles and responsibilities between the different technical administrative and extension tasks is common due to shortages of staff and this situation increases the workload of extensionists. At the regional level (CRDA) the division of extension and promotion of agricultural production (Fig. 1) is in charge of the program extension development and the coordination between the local CTVs. However, extension program development is supervised by the subdivision of plant production which is also in charge of the follow up of crop production campaigns. The multiplicity of the interlocutors within the CRDA for the extensionists explains their ambiguous roles. It should be emphasized that putting the extension with the promotion of agricultural production in the same administration has contributed to the marginalization of coaching and awareness activities in the areas of water, soil, forests, fisheries, investments, etc. Some voices are appealing for a re-engineering of the extension at the regional level by providing it with an independent administration to ensure its horizontal action.

Table 2 Human resource inventory for different agricultural establishments in Tunisia

	IRESA*	CRDAs**	AVFA	CTA	CTAB
Supervisors	1	24	1	1	1
Researchers/academics	821				
Ph.D. students	786				
Ph.D. and master students	456				
Administrative staff	275	24			8
Technical or specialized staff	715	72	15	15	11
Field Extension staff		628		5	
Workers	1200				

Source: IRESA/AVF inventory 2014 (*This inventory concerns all the agricultural and research institutes in Tunisia; ** this inventory concerns all the CRADAs CTVs and CRAs of Tunisia)

At the national level, the number of researchers and academicians was high compared to the number of extensionists (Table 2). Indeed, for financial reasons, many CRAs were deserted after the retirement of their coordinators; the number is still expected to decline with the early retirement plan planned by the government for the next five years. The census of the [22] confirms that only 42% of CRAs are currently functional. This indicates that the government pays more attention to the research axis as compared to extension, which is understaffed despite the decentralization efforts undertaken for its improvement. This was also reported by [25]. Women represent 28% of extension staff at the national level [22] and seem well involved in all the institutions according to the interviewees and are even the coordinators of some CTVs.

4.2 Barriers Related to Institution Linkages and Partnerships

The extension system is essentially based on the interdependent relationships among research labs, technical centers, CTVs and CRAs. Agronomic research centers and higher education institutions are often involved in international cooperation projects. This openness allows flow exchange of information among partners and facilitates the transfer of the generated knowledge. Nonetheless, they show few and weak connections with extension institutions and both of them had little cooperation with the private sector (Fig. 2). The private sector as the crop advisors have been show their effectiveness and could be considered as one of the most trusted information sources [26]. This form of traditional uncooperativeness isolates extension from the research and academic environments, which hinders the improvement of the dynamism of both knowledge co-production and the adaptive capacities.

It should be emphasized that the extension system suffers from the multiplicity of actors (CRDA, Researchers, OEP, AVFA, Technical Centers, Private Advisers, input suppliers, professional organizations, etc.). The legal arsenal in this area is silent about coordination, resources' pooling, and accountability. Collaboration between research and extension are often made through personal affinities as the non-autonomous status of the extensionists, who are under the tutorship of CRDAs, restricts the formal teamwork because of the slow pace of the administrative process to be undertaken for official cooperation. The interface institutions, AVFA, and technical centers (CTA, CTAB) work in close relation with both research and extension. However, IRESA is more involved with researchers than extensionists. At the international level, many conventions exist between research, academic and interface institutions on one side, and their counterparts in other countries and international donors on the other side. The extension is directly involved in a few international projects, and this aspect is being developed further because donors are increasingly imposing the involvement of development and extension agencies as a real socio-economic partner in the project activities. National and international project funding allow research institutions to increase their resource incomes from 10 to 60% of the total funding (according to the survey results). However no special funding is allocated to extension partners, which impact the extension staff motivation negatively. The lack of inadequate working relationship between research, extension and the ministry of agriculture was diagnosed in 1997 by the World Bank [27], which recommended the regionalization of research. The stagnant situation since 1997 reflects the inertia of the whole system which limits its ability to develop effective strategies for adapting to climate change.

The relationships between extension, interface, and research institutes on one side and the professional organizations such as farmer's syndicates, the Council of Engineers' Association, the Chamber of Agricultural Advisers on the other side are very weak and even absent. The low propensity of farmers to merge into mutual agricultural service companies or agricultural development groups seriously complicates the task of extension workers. Indeed, the stakeholders involving farmers are not yet strongly united under the pressure of political conflicts, especially after the popular Tunisian protests in 2011. They are still engaged by solving their day-to-day management problems and are not focused enough to contribute to the broader goal of getting improved agricultural technologies to all farmers, although associating farmers in knowledge co-production has proved its effectiveness in improving designing innovations and their adoption [28]. Weak links with markets and exporters were also noticed despite the importance of the exporting axis in citrus. This is also the case between research-extension systems and input supply firms, cooperatives and private advisory services. These poor connections, fostered by frequent conflicting interests, reflect the lack of exchange between commercial fields and the research-extension system. This unbalanced situation somewhat isolates the research system and causes a poor harmonization of the information about new technologies, decrease the level of trust in extension services and slows down rural social learning. The social capital, in this context, exerts little pressure to improve new technology adoption among farmers [29].

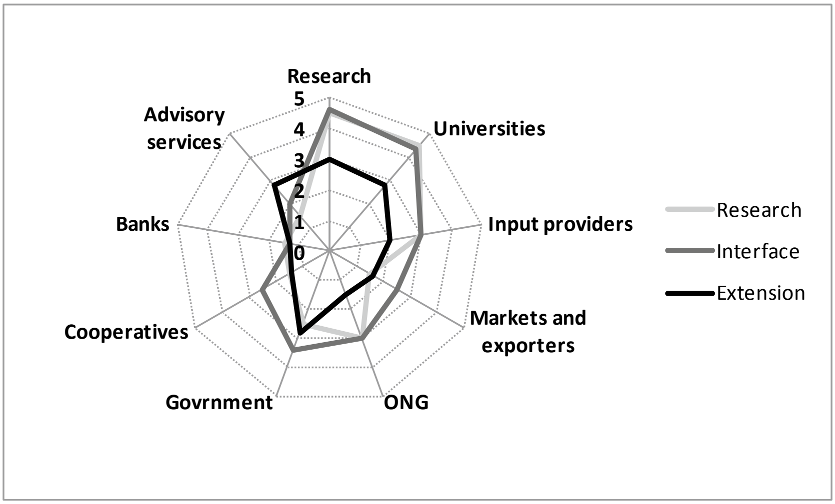

Fig. 2 Strength of linkages with the partnerships of the research, extension, and interface establishments (1: No linkage, 2: Weak linkage, 3: Moderate linkage, 4: Strong linkage, 5: Very strong linkage). Sources: Own elaboration from data analysis (2018)

4.3 Barriers Related to Time Allocation

Generally, the extension system allocated almost the same time to three main activities (Fig. 2):

- planning and support (program planning, preparing performance reports, in-service training, program evaluation, meetings, etc.),
- educational and advisory matters (farm visits, conducting on-farm demonstrations, training courses, workshops, field days, etc.),
- administrative services (data collection, delivery of authorization certificate to farmers for fertilizer provision, etc.).

However, in this structure, the time mobilized by administrative tasks is the highest compared to research and interface systems. Some CTVs complain about this and affirm that the administration can take up to 70% of their working time at the expense of the extension activities. It should be highlighted that extensionists are often occupied by daily activities contrasting with their original mission (food distribution for animals and ammonitrate, control of the anarchic houses in the rural landscape, contravention to the public hydraulic domain, uprooting of trees, illegal drilling, etc.) which requires mutual trust between farmers and extensionists. The interface, in contrary to research system, allocates more of their time to educational activities and advisory services and less time to planning and support activities. The administrative task overload constrains the extension workload. The lack of planning and support activities of the interface institutions – which could better inform other stakeholders

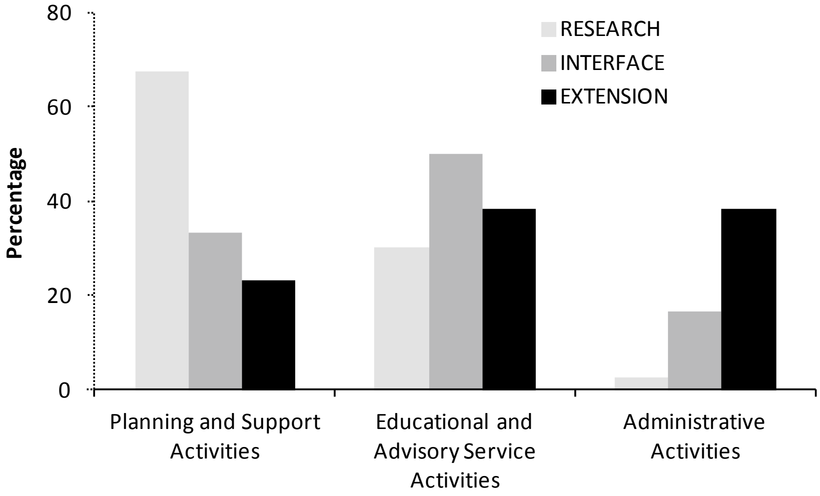

Fig. 3 Average allocation of time by staff of research, interface and extension institutions. Sources: Own elaboration from data analysis (2018)

-creates confusion in the research environment, which then impacts negatively on developing national strategies to enhance climate change resilience.

4.4 Efficiency of the Research-Extension Interface

Although the interfaces are organizationally designed to facilitate and accelerate the information transfer flow between extension and research, all the actors of this system have confirmed the absence of real exchange and feedback between the institutions. IRESA which has to gather the results of research outcomes, does not effectively do any classification or archival works. It only synthesizes the activity reports of the researchers in an annual report without any feedback to researchers. The evaluation of the research activities concerns only the research structures funded by the government as the research laboratories (formed by at least 12 persons), units (formed by at least eight persons), and actions (formed by at least two persons). This institution also does not have practical conventions with information provider institutions such as the National Institute of Meteorology to facilitate the access to climate data for their partners and the researchers under their tutelage. This limits the research and the analysis of the long-term assessments and impacts of climate change and favors short-term dynamics and reactions. Furthermore, interfaces do not have an updated email list of the researchers categorized according to their specialization which reflects the lack of formal accountability of the interface institutions, slows the dissemination of knowledge around new technologies, favors the redundancy in scientific research subjects and restricts the involvement and commitment of the different actors. In addition, many researchers and academicians do not use professional mail for practical and technical reasons, which further reduces the opportunities for collaboration through professional networks.

Although the interface institutions present the advantage of having national and international collaboration through funded projects, bureaucracy limits the effectiveness of institutional cooperation and stifles the system. They also do not have enough institutional authority and sufficient feedback from extension institutions and farmer organizations to orient the research staff towards the priority subjects dealing with the real agricultural problems, which lead to some delay in treating urgent agricultural production problems and few avant-garde and pro-active mechanisms elaboration facing climate change challenges.

The Technical Centers have the advantage of being structured in both specialized and complementary ways at the level of their tasks and are more solicited by researchers because of the easy implementation of field experimentations. In principle, Technical Centers are commissioned to carry out the up scaling and assess research results under field conditions. However, these practical collaborations reduce the field cooperation between extension and research bodies, which limits the extension of involvement in research projects. The AVFA and the Technical Centers are formally responsible for packaging research results for dissemination through various means including audio-visual and printed materials. However, all the interviewed extensionists attest to the ineffectiveness of the system to do so and make the research results accessible because of poor coordination with the interface institution (IRESA). Neither AVFA nor CTA has produced any written support on climate change, its impacts on water resources, and the advocated solutions for future well management. No technical documents were also produced on the citrus water requirements. Extension agents thus seek new knowledge from elsewhere including the internet and personal contacts which is not always meet with the specific need of farmers. The interface system is also characterized by a lack of effective communication skills (up-dated web, rapid communication about the call for projects, congress, etc.) which limits the flow of information exchange and the feedback between institutions.

5 Conclusion and Recommendations

Facing the rapid changing climate in a semi-arid context and with limited water resources, all of the Tunisian agricultural actors have to be aware of the critical situation and work together to achieve sustainable production systems. The extension institutions, which represent the front- line of action of the Ministry of Agriculture and present the advantage of involving many specialized structures and decentralization implementations, are not the only ones responsible for the success or failure of the national strategy of adopting new technologies for better adaptation towards change. Many other actors, such as research and interface institutions are also part of this responsibility. However, different barriers fragment agricultural institutions' capacities and their engagement is continually reactive instead of being proactive, which further enhances farmer mistrust and constrains farmers willingness to adopt new technologies. Lack of feedback, lack of accountability, bureaucratic obstacles and lack of flexible governance are the main barriers that prevent efficient linkages and participatory exchanges between the different institutions.

For this purpose, effective guidance policies are needed to enhance good coordination, access to information, and formal accountability. The administrative processes have to be modernized to alleviate or eliminate hindering bureaucratic rules such as the requirement to use hierarchical paper authorizations. The use of smart and updated working tools and methods such as the internet and e-mail based lists to facilitate the feedback flows between units and organizations would greatly improve extension's ability to disseminate knowledge to farmers. Collaborative arrangements can establish an efficient framework for managing linkages between the different actors, increase the flexibility of their coordination, and make from the hierarchical multi-institutionalized system a good opportunity of knowledge and data platform exchange.

Institutional websites have to be created and updated regularly to maintain the interest of farmers and enlarge the radius of social learning impact. Efficient packaging of the new technologies (production of practical document specialized well illustrated and simply explained, video on web site, etc.) has to be done to reinforce extension work. The extension services must be better supported, endowed with basic equipment for diagnosis and with computers, GPS, and vehicles to enable them to reach more farmers and to facilitate their tasks. They must be connected to the Internet and databases (water resources, pedology, agro-meteorology, investment, etc.). They have also to be provided with some autonomy in the decision-making process, involved more as a key partner in research and development projects, and strengthen their linkages with all the agricultural institutions, professional bodies, and environmental associations. Collaboration with the private sector as an industry that provides new technologies can generate benefits and reduce investment costs in this field. Water User Associations (GDAs), which supply the irrigation water to farmers at the local level, could be implicated in the dissemination chain by being involved in the sale of inputs to farmers that meet the objectives of research and extension. In this case, they could also improve their benefits, which could be reinvested in the maintenance and development of the local irrigation network system. Some credit allocation public organizations like the Agricultural Investment Promotion Agency (APIA) or agricultural bank, which give the financial incentives for farmers who adopt economic techniques of irrigation and train junior farmers investing in agricultural sectors, could collaborate with extension systems to assist investors. The extension system has to be strengthened by recognizing and organizing the status of the extensionists and alleviating them from the heavy, paper-based administrative tasks. Most of the guidance require better governance and modernization of the workings of administrative operations rather than significant funding.

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Stable Isotopes for Sustainable Management of Agricultural Water: Case of Mateur Plain (North Tunisia)

Najiba Chkir, Messaouda Yermani, and Kamel Zouari

Abstract Water stable isotopes have been used since the 61's as natural tracers of the hydrological cycle. Water entering a catchment have a characteristic fingerprint of its origin and therefore can help to identify where the water in the system comes from. A multicriteria approach in studying hydrodynamics of a multilayer aquifer system has been used in the Mateur plain (Northern Tunisia). It aims to reconstruct the hydrogeological framework of the shallow and the two-deep aquifers distinguished in this area and then to define their hydrochemical and isotopic features. In order to determine the hydrogeochemical processes controlling the water quality and origin, 70 samples from surface water, springs and groundwater were collected and analyzed for various parameters. Physical and chemical parameters of groundwater such as electrical conductivity, pH, total dissolved solids, Na, K, Ca, Mg, Cl, HCO_3, SO_4, Sr and water molecule isotopes ($\delta^{18}O$, δ^2H and ^3H) were determined. This dataset reveals that water chemistry is regulated primarily by the combination of three processes: (1) weathering of minerals such as silicates and calcites; (2) ion reverse exchange with host rocks, and (3) mixing with Cl-rich water from the Lake Ichkeul. Saturation indices calculated by PHREEQC model show that nearly all water samples were saturated to undersaturated with respect to carbonate and evaporite minerals. Mixing between all water masses of the system (shallow, deep groundwater, surface water and springs) is indicated by homogeneous values of $\delta^{18}O$ and δ^2H contents. Isotopic composition plotted close to the Global Meteoric Water Line confirms that groundwater is mostly recharged by modern precipitation with an evaporation effect revealed by d-excess values mainly around the Lake Ichkeul in relation with the wet/dry fluctuation of the surrounding swamp. Tritium analysis confirmed the presence of modern groundwater and a relatively homogeneous

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recharge process. On the other hand, groundwater sampled in intensive farming areas have nitrate contents exceeding World Health Organization (WHO) standards indicating that the long-term agriculture activities are affecting groundwater quality.

Keywords Agricultural basin · Hydrogeochemistry · Water/rock interaction · $\delta^{18}O$ · $\delta^{2}H$ · Nitrate

1 Introduction

To meet the ever-increasing water demand in the world, groundwater is being extensively used to supplement the available surface water. In Tunisia, groundwater is highly valued for drinking and irrigation purposes because large parts of the country have little access to surface water due to rare and irregular precipitations. Water quality is a vital concern for mankind since it is directly linked with human health. Since it is naturally protected, groundwater has been long time considered as immune from contamination. However, it has been reported that in most of the agricultural plain of Tunisia, the problem of groundwater quality deterioration has become urgent because of the increasing exploitation, the intensive farming and therefore the water contamination by intensive use of fertilizers. In many regions, the quality is worsening with sometimes serious irreversible consequences. Reliable information on water quality is therefore imperative to support an effective management that prevent and control water pollution.

Commonly, chemical parameters of groundwater are used to classify and assess water quality [1–3]. Further, it is possible to understand the change in quality due to rock-water interaction or any type of anthropogenic influence [4–6]. Isotope hydrology partially fills the gap related to spatial and temporal variability by providing information on type, origin and age of the water. For that purpose, naturally occurring constitutive isotopes of the water molecules (^{18}O, ^{2}H, ^{3}H) are well suited since they represent the best tracers of water history insight to aquifers. During the past four decades, there has been a major expansion in the number of environmental studies bases on stable isotopes as tracers, either of material sources or insight processes. These tracers are widely and extensively used in groundwater investigations to address problems related to recharge, delineation of flow systems and quantification of mass-balance relationships. Existing isotope hydrology studies have considerably contributed to improve the comprehension of the different processes that control water dynamics within the hydrogeological basin. Earlier studies using stable isotopes focused on the identification of the sources and origin of water, the mapping of palaeowaters, the delineation of hydraulic interconnections between different aquifer and the estimation of rate of direct recharge to the groundwater from precipitation [7–11]. Isotope application to problems associated with the impact of humans on water resources had also been conducted and had provided significant contribution to the assessment and monitoring of sources and processes of water pollution such salinization in coastal aquifers [12–17].

This chapter aims to contribute to an improved understanding of the hydrochemistry and hydrogeology of the detrital aquifer of the Mateur Plain (Northern Tunisia) in order to identify natural and human-induced processes which control the hydrochemical zoning within the aquifer system and therefore to support a sustainable groundwater abstraction. These objectives have been achieved using geochemical and environmental isotopes in the complement of physical hydrogeology.

2 General Concepts of Isotope Hydrology

Environmental isotopes are nowadays routinely used in geochemical and hydrogeological investigations. Stable isotopes techniques became more and more cost-efficient in comparison with some classical hydrological techniques. Also, isotopes often provide information that sometimes could not be obtained by other techniques, in particular in arid areas and in areas with the short or lacking dataset. Isotopes techniques are based on the general concept of "tracing" using either naturally occurring isotopes (environmental) or injected artificial isotopes. Environmental isotopes are more commonly used since they allow studying "various hydrogeological processes on a much larger temporal and spatial scale through their natural distribution in a hydrological system" [14]. The use of artificial tracers generally is effective for site-specific, local applications.

Environmental isotope methodologies, in particular, those based on the water molecule isotopes, are effective in regional studies of water resources to obtain time and space-integrated characteristics of groundwater systems. Oxygen and hydrogen isotopes of water provides an excellent tool for evaluating hydrogeological processes such as precipitation origin, groundwater origin; groundwater age, velocity and direction of flow; interrelations between surface waters and groundwater; renewable rates of aquifers, possible interconnections between different aquifers [9, 10, 14, 18–25].

The basic principles of water isotopes tracers applied for groundwater studies are presented in this chapter. More details on different applications are provided though included references.

2.1 Water Isotopes

All substances are constituted of chemical elements characterized by the number of protons (Z) included in the atom (Z = atomic number). In order to balance the positive charge of protons, electrons that are negatively charged orbit around the nucleus. Thus, Z is the number of protons as well as electrons in an atom. The nucleus also includes neutrons that have approximately the same mass of protons. The atom weight given by that of the nucleus, determine the element's mass number A: mass number = protons + neutrons. Isotopes are different forms of the same atom that differ only in their number of neutrons. Many elements, such as carbon,

Table 1 Natural isotopic abundances of the water molecule

Element	Isotopes	Z	A	Abundance (%)	
Hydrogen	^{1}H (Protium)	1	1	99,9844	Stable
	^{2}H (Deuterium)	1	2	0,0156	Stable
	^{3}H (Tritium)	1	3	Trace	Radioactive—Half-life = 12.32 y
Oxygen	^{16}O	8	16	99,759	Stable
	^{17}O	8	17	0,037	Stable
	^{18}O	8	18	0,204	Stable

oxygen, hydrogen, chloride, have multiple naturally occurring isotopes. Due to the same numbers of protons and electrons, different isotopes of an element generally have the same chemical properties. For most elements, usually, one isotope is the predominantly abundant isotope. The less abundant stable isotopes of an element are heavier than the more common ones because they have one or two additional neutrons than protons. Isotopes can be either stable or radioactive.

The most relevant isotopes for atmospheric and hydrologic sciences are those of the water molecule, meant ^{18}O and ^{16}O for oxygen and ^{3}H, ^{2}H and ^{1}H for hydrogen [9, 26]. Table 1 outlines the average isotopic abundances that are most commonly measured for water stable isotope measurements.

The stable isotopic compositions of low-mass elements such as oxygen and hydrogen are normally reported as "delta" (δ) values in parts per thousand (denoted as ‰) enrichments or depletions relative to a standard of known composition. δ values are calculated by:

$$\delta = 1000\frac{\left(R_{sample} - R_{standard}\right)}{R_{standard}} \text{ (in } ‰)$$

where "R" is the ratio of the rare (heavy) to the abundant (light) isotope in the sample or standard. For the elements oxygen and hydrogen, the average terrestrial abundance ratio of the heavy to the light isotope ranges from 1:500 (oxygen) to 1:6410 (hydrogen). When the sample contains more heavy isotopes than the standard, the δ value is positive; while it's negative when the sample contains less of heavy isotopes than the standard.

For isotope hydrology applications, the International Atomic Energy Agency (IAEA, Vienna) regularly published and distributed the Vienna Standard Mean Ocean Water (V-SMOW), an average of different ocean samples from around the world that is considered as the usual standard.

$$R_{standard}\left(\frac{\text{O18}}{\text{O16}}\right) = (2005.2 \pm 0.45)10^{-6} \text{ and } R_{standard}\left(\frac{\text{H2}}{\text{H1}}\right) = (155.76 \pm 0.07)10^{-6}$$

Isotopic compositions are determined in specialized laboratories using isotope ratio mass spectrometry or more recently laser spectrometry [27]. The analytical precisions are small relative to the ranges in δ values that occur in natural earth systems [27]. Typical one standard deviation analytical precisions for oxygen are in the range of 0.05‰ to 0.2‰; typical precisions for hydrogen isotopes are poorer, from 0.2 to 2.0‰, because of the lower ^{2}H:^{1}H ratio [27].

2.2 Isotopic Fractionation

Both heavy and light stable isotopes participate in chemical reactions and geochemical processes. However, due to stronger chemical bonds and attractive forces of atoms in the heavy stable isotopes than in the common lighter ones, the heavier isotopes react more slowly in both physical and biological reactions what explain the isotopic separation or fractionation between reactant and product. As a consequence of fractionation processes, waters often develop unique isotopic compositions that may be indicative of their source or of the processes that formed them. Two different types of processes cause isotope fractionation; equilibrium and kinetic isotope effects.

– Equilibrium isotope-exchange: These reactions are associated with the redistribution of element isotopes among various phases. At equilibrium, the bidirectional reactions of any particular isotope have equal rates thus the ratios of the different isotopes in each compound remains constant. During equilibrium reactions, the heavier isotope generally accumulates in the higher energy state specie. During phase changes, the ratio of heavy to light isotopes in the molecules in the two phases varies. For example, during water vapor condensation, the heavier water isotopes (^{18}O and ^{2}H) become enriched in the liquid phase while the lighter isotopes (^{16}O and ^{1}H) tend toward the vapor phase [26].
– Kinetic isotope fractionation: It occurs in systems where the bidirectional reaction rates are not identical. If the reaction products become isolated from the reactants, the reactions may be unidirectional. As a general rule, the lighter isotopes react more easily than the heavy isotopes. Therefore, the residual reactants become enriched in the heavy isotopes and the lighter isotopes become concentrated in the products. Kinetic fractionations results are much larger than the equivalent equilibrium reaction [26].

Most reactions are equilibrium isotope-exchange affected by an additional kinetic isotope fractionation. For example, evaporation takes place under purely equilibrium conditions at 100% relative air humidity, but typically the vapor becomes partially isolated from the water surface when transported away by turbulent processes. The equilibrium of the phase change reaction is forced towards one side, and therefore, the isotopic compositions of the water and vapor are affected by an additional kinetic isotope fractionation of variable magnitude [26].

The partitioning of stable isotopes between two substances A and B can be expressed by use of the isotopic fractionation factor (α) [26]:

$$\propto_{A-B} = \frac{R_A}{R_B}$$

where R is the ratio of the rare to abundant isotope ($^2H/^1H$ or $^{18}O/^{16}O$).

The fractionation factor α is related to δ values by the following equation:

$$\propto_{A-B} = \frac{(1000 + \delta_A)}{(1000 + \delta_B)}$$

Values for α tend to be very close to 1. The sign and magnitude of α are dependent on many factors such as chemical composition although temperature remains the most important one. The equilibrium fractionation factors (α_{l-v}) for the water liquid–vapor phase transition are 1.0098 and 1.084 at 20 °C for ^{18}O and ^2H, respectively [28]. In both cases, $\alpha_{l-v} > 1$, which means that the liquid water is heavier than the vapor phase: the $\delta^{18}O$ of water is +9.8‰ higher than the $\delta^{18}O$ value of vapor at equilibrium [28].

2.3 Isotopes in the Water Cycle

The hydrological cycle as a result of the combination of several processes like precipitation, evaporation, transpiration, deposition, runoff, infiltration and groundwater flow, is continuous water storage and transfer between the biosphere, atmosphere, lithosphere and hydrosphere. The two main phase changes that control the hydrological cycle are condensation and evaporation during which equilibrium isotope-exchange as well as isotope fractionation take place and apply a specific fingerprint to the meteoric water (Fig. 1). On the other hand, stable water isotopes can be considered as conservative in groundwater as long as no phase changes or fractionation occur along the flow-path. The stable isotopes composition of groundwater will maintain almost the same as the input meteoric water [10]. Accordingly, the comparison of stable isotopes composition of groundwater and meteoric water provides an efficient tool for evaluating the aquifer recharge mechanisms such as modern recharge, interactions between surface and groundwater, mixing processes [29, 30–33].

Therefore, the input signal should be defined at a regional scale in order to allow a comprehensive overview of groundwater distribution. The distribution of isotopes composition in rainfall is governed by a variety of physical processes mainly controlled by the weather system [34]. The interpretation of global and seasonal variations of stable isotopes composition in precipitation is based on [35] five empirical isotope effects related to various complex factors of the global hydrological cycle: Isotope signal in precipitation gradually depleted towards higher latitudes, increasing altitude, increasing distance from the coast, higher precipitation amounts and is affected by a seasonal variation. These isotope effects cannot be attributed to one single meteorological causes, but it is mainly interpreted as a temperature-related effect on the isotopic fractionation. Some other factors such as precipitation

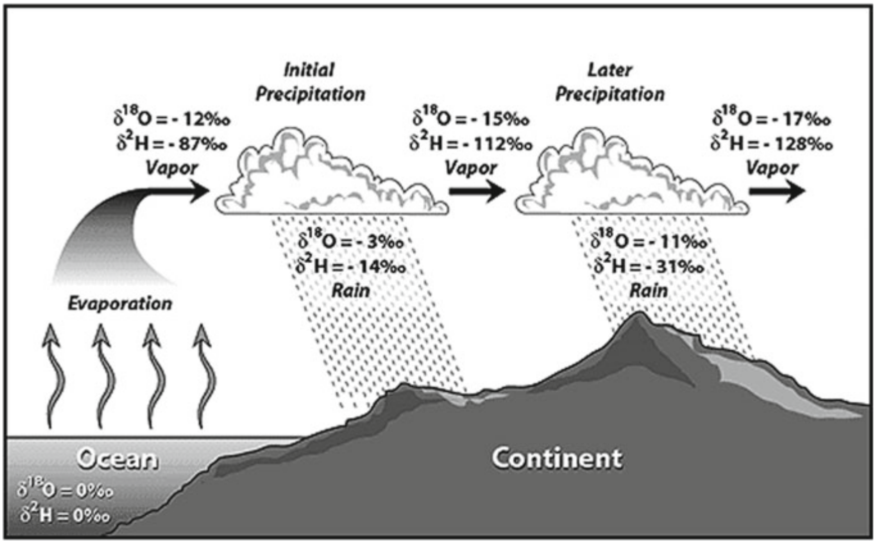

Fig. 1 Main fractionation steps and typical values of oxygen ($\delta^{18}O$) and deuterium (δ^2H) in a temperate climate (Figure taken from https://web.sahra.arizona.edu/programs/isotopes/oxygen.html)

type (convective, frontal), air origin, or condensation altitude, moisture advection are also controlling these effects [35].

The mean state emerging from the superposition of weather-induced isotope signals is reflected by the worldwide relationship between $\delta^{18}O$ and δ^2H values for precipitation that plot along the global meteoric water line (GMWL) (Fig. 2) defined by [35] as follows:

$$\delta^2H = 8 * \delta^{18}O + 10‰$$

This model has been refined by [36] through the long-term observations made within the framework of the IAEA/WMO Global Network for Isotopes in Precipitation (GNIP) by the relationship:

$$\delta^2 H = 8.17(\pm 0.07) * \delta^{18} O + 11.27(\pm 0.65) \pm ‰$$

The 8 slope of the meteoric water line of oxygen and hydrogen isotopes represents the ratio of the temperature relationship between ^2H and ^{18}O when condensation occurs at equilibrium conditions. The intercept, called deuterium excess or d-excess ($d = \delta^2H - 8\delta^{18}O$) [37] is about 10% in most places around the world. The value of intercept is affected by variations in atmospheric circulation and the corresponding changes of moisture source locations [38–41].

Local Meteoric Water Lines (LMWL) based on local precipitation measurements of at least 1-year period are commonly plotted as a linear δ^2H-$\delta^{18}O$ relationship

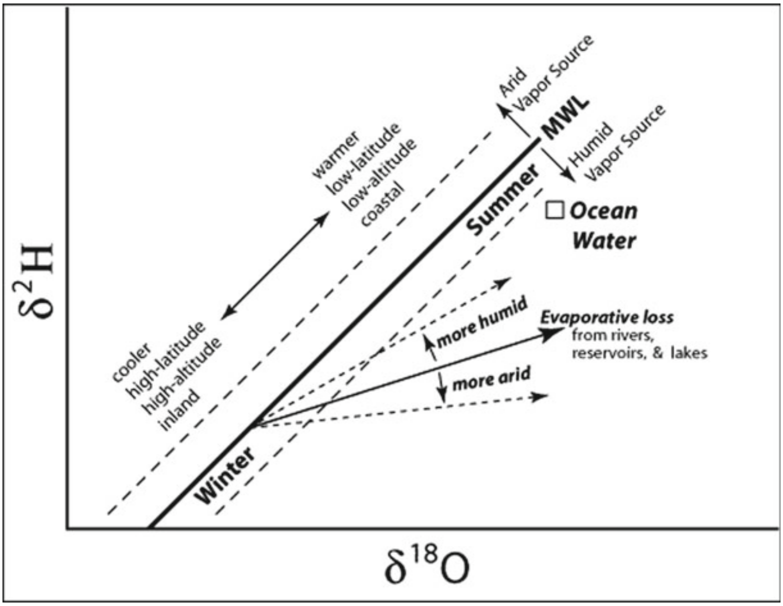

Fig. 2 Schematic meteoric water line indicating different factors of deviations from $\delta^{18}O$-$\delta^{2}H$ relationships (https://web.sahra.arizona.edu/programs/isotopes/oxygen.html)

parallel to the GMWL (8-slope line) in order to involve the regional scale in groundwater studies. LMWL that reflect variation in climate, rainfall seasonality and geography are discussed according to the deviation of the d-excess [42, 43]. Some studies have used d-excess to identify the air mass source of meteoric water and to define the seasonal recharge of groundwater [21, 41–46]. For arid regions where the vapor source originates from low humidity air masses, d-excess values will be higher than 20 [45, 46].

3 Case Study of the Mateur Plain (Northern Tunisia)

The plain of Mateur is one of the most important aquifers in northern Tunisia. Groundwater is mainly used for agricultural purposes and secondly for drinking water supply. The plain is historically dominated by intensive agriculture of cereals and livestock. The agricultural development is mainly based on high exploitation rate of groundwater and intensive use of fertilizers. Therefore, many problems have arisen during the last years in relation with groundwater degradation and contamination. This investigation is carried out in order to identify the groundwater state of the Plain of Mateur which would help decision-makers and farmers to include this information in their water-related activities.

3.1 Site Description

The alluvial Mateur Plain (250 Km^2), a part of the catchment (2080 Km^2), is crossed by an important hydrographic network. This plain is bordered east by the horsts of Messeftine, Melah and El Assafir, south by Jebel Sidi Beni Daoued, west and north-west by the Plateau of Safsaf and Jebel Kef Nsour, and north and north-east by the Lake Bizerte (Fig. 3). The Plain of Mateur and the Lake Ichkeul constitute the endoreic discharge area of all surrounding catchments.

The Mateur plain, submitted to a sub-humid climate dominated by north western winds, is one of the rainiest regions of the country. Annual precipitation average is about 564 mm for 120 rainy days with a high irregular inter and intra annual distribution. Despite the sea proximity, the continental effect is quite marked due to the surrounding reliefs. Temperatures range between 15 and 28 °C with a mean of 18 °C. Two seasons are distinguished i) a rainy cold winter with temperature ranging between 11 and 16 °C, high precipitations and rivers flooding, and ii) a hot dry summer from May to October with temperature ranging from 20 to 28 °C and high evaporation rates The annual evaporation rate is about 932 mm ranging between 776 and 1074 mm. Renewable water resources are estimated at 8 10^6 m^3 per year with an exploitation rate of 79%.

The Mateur Plain is a collapsed basin filled by deltaic and fluvio-lacustrine deposits of the several wadis (local name of non-perennial rivers) crossing the plain and discharging in the Lake Ichkeul. The sedimentation is characterized by a cross-stratification and a lenticular structure [47]. Deposits are mainly of Late Quaternary (Fig. 4) while the substratum is constituted by Triassic and Upper retaceous marls and limestones with a large spatial variation. Oldest formations outcropping in north and northwestern bordering reliefs are mainly Triassic with abnormal contact with Jurassic, Cretaceous, Paleogene and Neogene series. In northern Tunisia such as

Fig. 3 The Mateur Plain and its surrounding reliefs (Google Inc. 2020—Google Earth Vers. 7.3.3.7786) (Chkir et al. 2020)

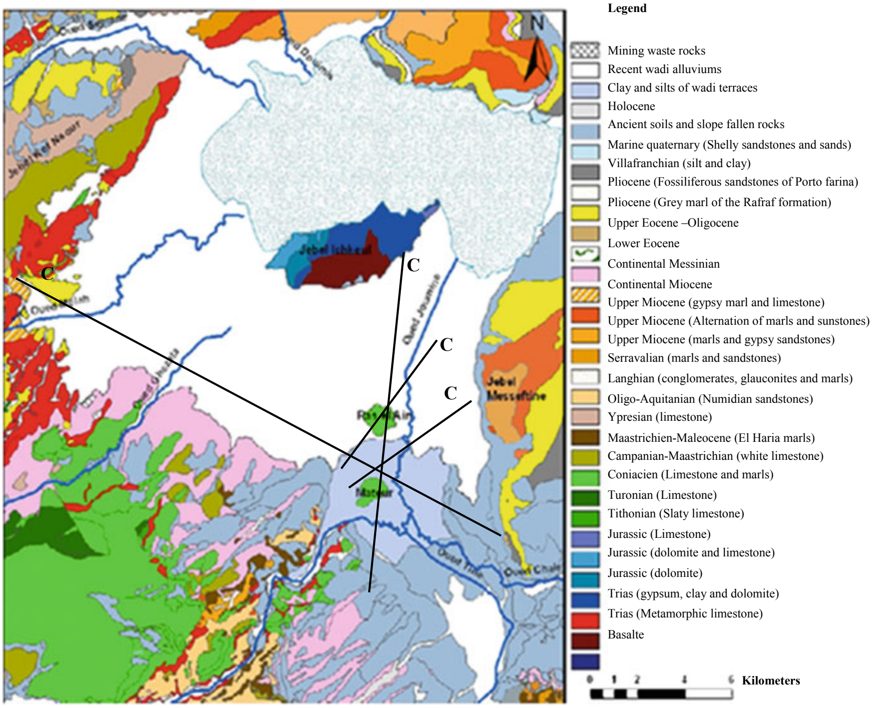

Fig. 4 Geological map of the Plain of Mateur (Chkir et al. 2020)

Jebel Ichkeul, it is presented either as diapiric structures or as salt glacier structures. The Triassic deposits are characterized by a chaotic aspect consisting of gypsiferous, clayey, carbonated and locally sandy facies [48, 49]. Jurassic outcrops, dominantly made of calcareous series with some marly intercalations, are only observed at the Jebel Ichkeul on the central part of the plain. It is.

The sedimentary system is underlying the plain lodges three locally interconnected aquifers. The shallow aquifer lodged in the upper quaternary alluvium covers the entire plain. A second aquifer is lodged in the deeper layer of the Quaternary alluvium and is separated from the shallow aquifer by muddy layer. This aquifer is mainly located in the north-western part of the basin. A second deep aquifer, lodged in Campanian limestones, is only tapped in the proximity of Mateur and Ras el Ain areas, in the southern part of the basin. Data obtained through electrical prospecting and hydrogeological drilling have been used to define the reservoir geometry of the shallow and deep aquifers and showed the complexity of the aquifer system induced by an active tectonic and heterogeneous stowage [49]. Thick and coarse deposits induced by flooding periods are located upstream of the basin while finest ones are deposit far away downstream the basin. The thickness of the clayey layer varies from 2.6 m upstream to 15.5 m downstream [48]. Surface and subsurface geological data allow distinguishing three important detrital alluvial zones:

- Between the hill of Mateur and the eastern border of the plain, the stowage of the plain is due to detrital deposits of the hydrographic network (wadi Tine) and the foothill of eastern mountains (Fig. 5b: C2 transect).
- At the western side of the Hill of Mateur, alluviums are thicker and coarser and are in contact through a fault with Campanian limestones (Fig. 5b: C2 transect and Fig. 5d: C4 transect). This area corresponds to the ancient delta cone of the wadi Joumine. South of Ras El Ain, deposits became finest (loam, clay and marls) (Fig. 5c: C3 transect).
- Close to wadi Ghezala and wadi Melah, at the northwestern part of the basin, alluvial deposits show greater thickness and extension. Permeable formations extend along main riverbeds as lenticular series. The alluviation is supported by the Oligocene sandstones foothills at the western border of the basin.

The substratum is constituted of marly limestone buried under alluvium at the left riverside of the wadi Joumine. While, the substratum of the right riverside is Triassic and carries the Campanian limestone (Fig. 5a: C1 transect). Around the hills of Mateur and Ras El Ain, the limestone substratum had been continuously observed. However, far away east and west, the substratum becomes deeper likely related to two normal faults (Fig. 5b: C2 transect, Fig. 5d: C4 transect). Eastern the hill of Mateur, the substratum becomes thicker as Miocene marly and saliferous formations while western this hill, the substratum is made by grey to yellow compact clayey bed with a thickness ranging between 9 to 66 m. South of the Hill of Ras El Ain hill, Campanian limestone constitutes a synclinal structure which is locally the substratum of the shallow aquifer [48]. North, the limestone roof seems to become under the alluvium as shown by the Fig. 5a (C1 transect). Lower Senonian marls constitute the hydrogeological substratum of the Deep Campanian Aquifer in all the zone of the hills of Mateur and Ras el Ain.

3.2 Materials and Methods

The key steps of the investigation are presented as a flow-chart in Fig. 6.

The sampling network covers the entire basin. Special attention has been paid to sample the different lithological formations, at different depths, and to cover the recharge and discharge zones of the multilayered aquifer. Thus, the data can be assumed as representative of most of the geochemical processes that take place in the aquifer. About 70 samples were collected during a high water period from 42 wells, 5 springs, 19 boreholes, 4 surface waters referred hereafter to respectively P, A, S and ES points (Fig. 7).

Groundwater sampling was performed according to standard protocols employed for routine monitoring onsite. Before all sample collection, the wells were pumped for about three to five minutes until temperature, specific conductance, and pH stabilized. This was to ensure the collection of representative samples. Samples were collected in three (3) labeled, well drained polyethylene containers tightly corked.

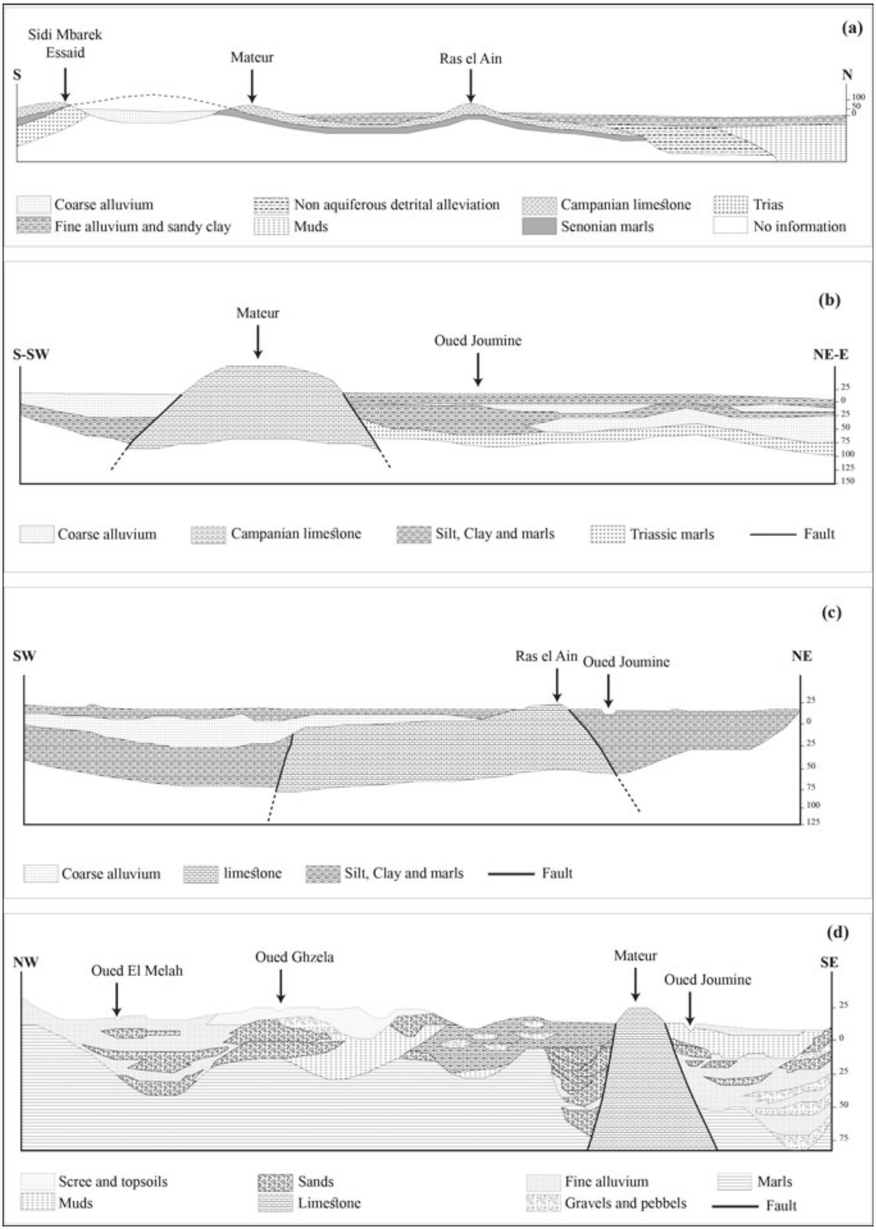

Fig. 5 Lithostratigraphic transects through the Plain of Mateur (a) C1 N-E transect through Ras el Ain-Mateur-Sidi Mbarek Essaid; (b) C2 NE-SW transect through Mateur area; (c) C3 transect through Ras El Ain area NE-SW; (d) C4 NW-SE transect through the plain of Mateur (Chkir et al. 2020)

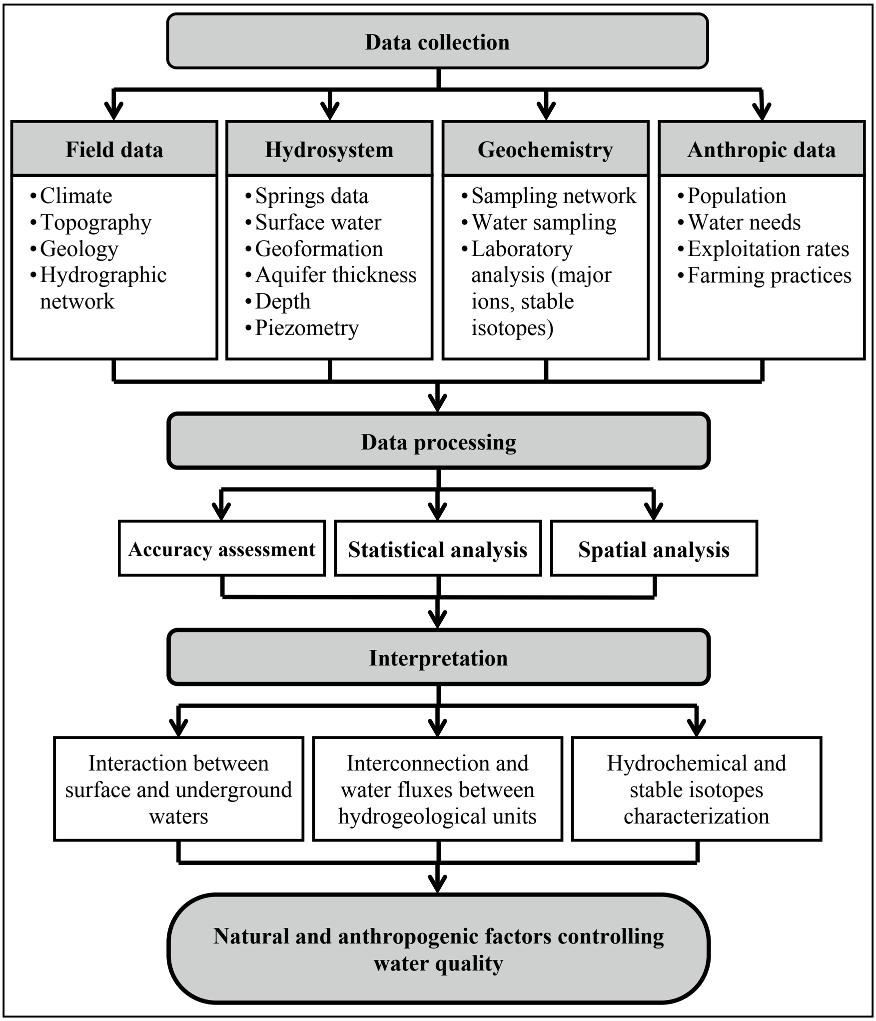

Fig. 6 Flow Chart of the Hydrogeological and geochemical investigation methodology (Chkir et al. 2020)

The choice of polyethylene containers is to minimize contamination that could alter the water constituents. The first container was 250 ml for stable isotopes analyses. The second container (1 L container) was used for cations determination; two (2) drops of concentrated nitric acid (HNO_3) are added to this container in order to homogenize the sampled water and to prevent absorption/adsorption of metals to the wall of the container. Acidification is used to stops most bacterial growth and to inhibit oxidation reactions as well as cations precipitation. The third plastic container (1 L) was used for anion determination. These samples were preserved in cool boxes to keep the temperature below 20 °C during the transfer to the laboratory for analysis

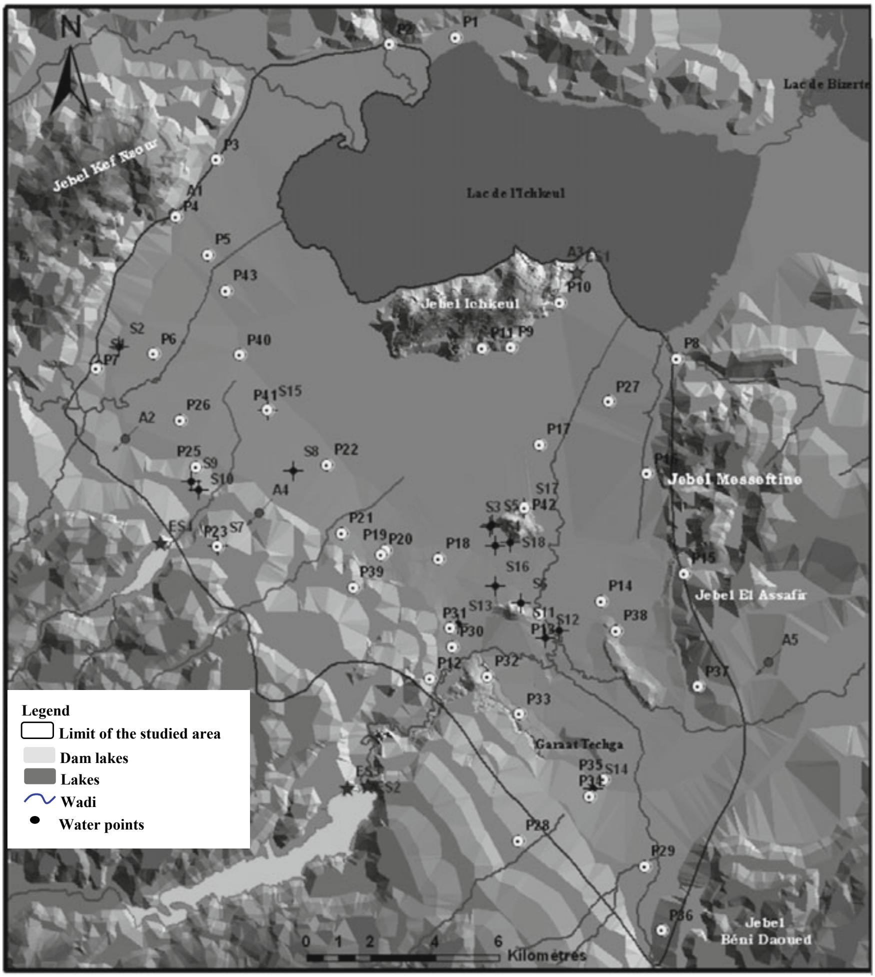

Fig. 7 Sampling network over the Plain of Mateur (P: wells, A: springs, S: boreholes, ES: surface waters) (Chkir et al. 2020)

within the stipulated period. Before sample collection, the containers were cleaned with diluted nitric acid and distilled water, properly rinsed with the borehole water to be sampled, filled to the brim, tightly covered to retain the CO_2 of the collected water and to avoid contamination. Water collection was carried out during good weather conditions in order to prevent the contamination of sampled water by precipitation and to preserve its quality.

Conductivity, pH and temperature measurements of waters were routinely determined in the field during sample collection using an HI 9828 Multiparameter. Volumetric titrations were performed to determinate the bicarbonate alkalinity. The static water table (SWL) in each of the sampling locations as well as the total depth penetrated by the boreholes was equally recorded, when possible. A Global Positioning System (GPS) unit, portable GARMIN 76, was used for recording coordinates and elevation readings.

Chemical analyses of major elements (Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, $SO_4{}^{2-}$, $HCO_3{}^-$) and Sr^{2+} were carried out in the Laboratory of Radio-Analyses and Environment of the National School of Engineers of Sfax (Tunisia) after samples filtering through 0.45 μm acetate cellulose filter. Major elements and nitrates have been analyzed by Liquid-Ion Chromatography (HPLC) on a Water Chromatograph equipped with columns IC-PakTM CM/D for cations, using EDTA and nitric acid as eluent, and on a Metrohm chromatograph equipped with columns CI SUPER-SEP for anions using phthalic acid and acetonitric as eluent. The overall detection limit for ions was 0.04 $mg.l^{-1}$. The total alkalinity (as $HCO_3{}^-$) was determined by titration with 0.01 or 0.1 HCl against methyl orange and bromcresol green indicators. Trace elements had been analyzed by atomic absorption spectroscopy (AAS). Salinity represents the total dissolved salts (TDS) noticed in the Laboratory. It is defined as the concentration of dissolved salts in water directly obtained after drying 100 ml of the sample in an oven at 105 °C for 24 h. It corresponds to the mass difference and is expressed in $g.l^{-1}$.

The chemical analyses quality was also checked. The results were tested for charge balance error according to [50]. For all the samples, analytical error as inferred from the balance between cations and anions did not exceed 5%.

Major elements were plotted on the piper diagram in order to identify water chemical facies. Relationships with the total mineralization were investigated for all dissolved ions. Bivariate diagrams are plotted to investigate the causes and mechanisms of the geochemical processes controlling water mineralization and quality. The Diagram software based on the speciation model PHREEQC [5] was used to calculate saturation indices of common minerals in such geographical context as anhydrite (SI_a), gypsum (SI_g), halite (SI_h), calcite (SI_c) and dolomite (SI_d). A saturation index (SI) is the ratio between the $\log_{10}$ of the ionic activity product of components of a mineral and the equilibrium constant of this mineral at a given temperature. The thermodynamic data used in this computation were those contained in the default database of the PHREEQC model. If the SI is < 1, dissolution is considered as the dominant process for the related mineral, and when the SI is > 1, precipitation of the mineral is likely to be occurring in the system [50]. Some minerals would precipitate slowly at low temperature whereas others such as calcite precipitate at greater rates at common groundwater temperature. Stable isotopes (^{18}O, ^2H) were measured by laser spectrometry (Los Gatos Equipment) and reported in the usual δ notation relative to Vienna Standard Mean Oceanic Water (‰VSMOW). Typical precisions are ±0.1‰ and ±1.0‰ for the oxygen 18 and the deuterium, respectively.

3.3 Water Levels and Flow Pathways

3.3.1 Shallow Aquifer Flowpaths

The piezometric map of the shallow aquifer produced by usual krigging of 45 piezometric measurements carried out at the end of the wet season (March) shows that water flows according to the topographic levels from the bordering reliefs toward the central part of the basin (Fig. 8). Water levels tend to reach the earth surface at the proximity of the northwest shore of the Lake Ichkeul (0.65 m and 0.72 m depth

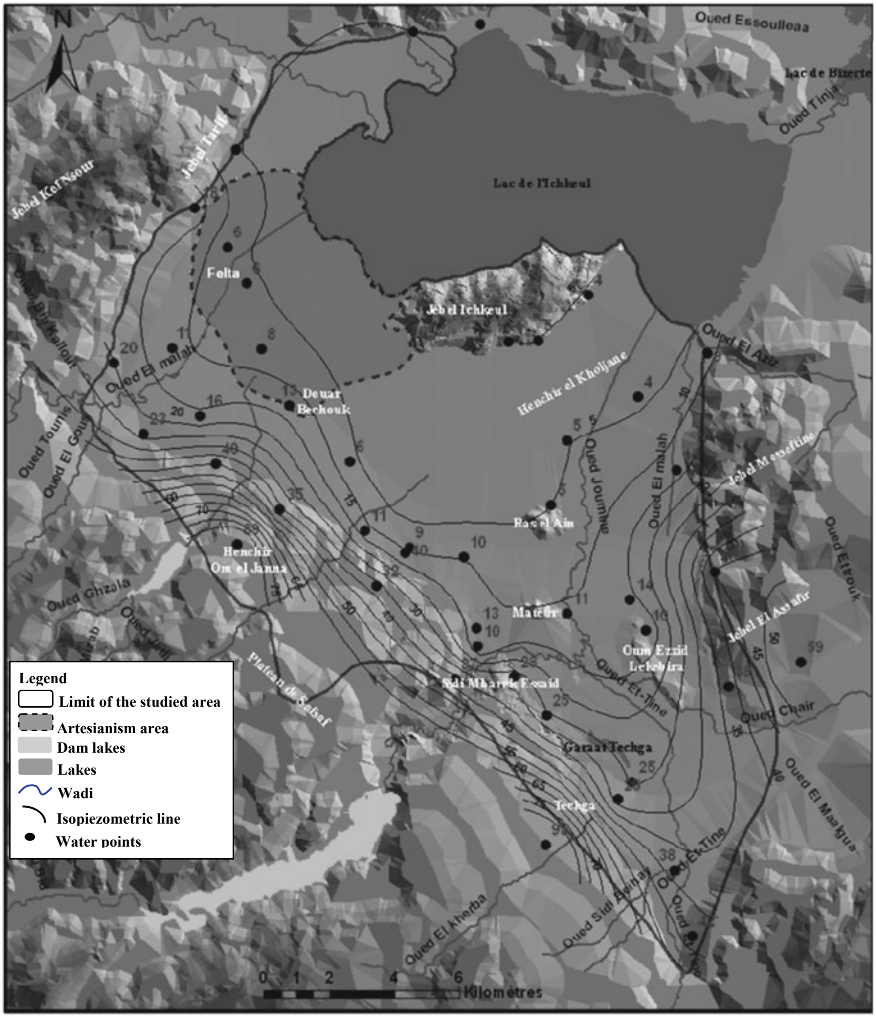

Fig. 8 Piezometric map of the shallow aquifer lodged in quaternary alluvium (Chkir et al. 2020)

respectively for P26 and P17), and an artesianism zone is observed in the central part of the basin from the Douar Bechouk and Felta areas toward the Lake.

The radial piezometric contours reveal different hydrological recharge areas and a NW flow direction with wider water table contour spacing in the central part of the basin. The contribution of the different wadis is marked around the basin: wadi Chair and Tine southeastern and wadi Ghezala and Melah western. The contribution of wadi Joumine to the recharge of the aquifer is covered by lateral runoff of the plateau of Safsaf given that the Joumine dam has reduced its stream flow through the plain. However, this wadi continues to drain the shallow aquifer in the central part of the plain, at the Henchir el Kholjene area, where a secondary recharge area could be explained by Jebel Ichkeul. The hydraulic gradient broadly decreases downstream toward the central part of the plain. Highest values are observed between the wells P22 and P23 (34 10^{-3}), between the wells P28 and P34 (26 10^{-3}) and at the Jebel Messeftine (14.5 10^{-3}). These values are explained by high slopes of the bordering massifs. Downstream, in the central part of the basin, the hydraulic gradient decreases to 1.6 10^{-3} around Ras el Ain areas, south of Jebel Ichkeul, where water flows very slowly toward the Lake. These low values are related to the fine granulometry and the important thickness of the alluvium stowage. Assuming that the aquifer has no underground outlet, the discharge should only take place by evaporation or by Joumine and Melah wadis drainage. These conditions contribute to protect the aquifer against a rapid depletion and the intrusion of the saline waters of the Lake Ichkeul in case of over-exploitation.

The piezometric levels of the shallow aquifer seasonally vary according to climate conditions and to human pressure. During the wet season, precipitation contributes to the recharge of the aquifer while evaporation enhanced by intensive groundwater abstraction during the drought season induces a high drop of the water table. However, the lag time observed between the external pressure and the aquifer response had been explained by the duration of water percolation through the unsaturated zone. A long lag time of about two months observed at the piezometer P12 situated in the central part of the basin has been explained by the clayey soils covering the plain. A short time-step monitoring of the piezometry should be carried out to refine this lag time and to apprehend its spatial variability.

3.3.2 Deep Aquifers Flowpaths

Due to inexistent data and difficult access conditions to boreholes, only one piezometric transect has been studied for the Quaternary Deep Aquifer (DQA). This transect (Fig. 9) shows that the piezometric levels follow the topography but remains under the shallow aquifer levels. In the central part of the basin, the DQA also becomes artesian. The piezometric data of the Deep Campanian Aquifer show that water flows from Mateur toward Ras El Ain area. In the upslope area, piezometric levels correspond to those of the shallow aquifer, the positive difference between the shallow aquifer and the Deep Campanian Aquifer increases downstream above 4 m

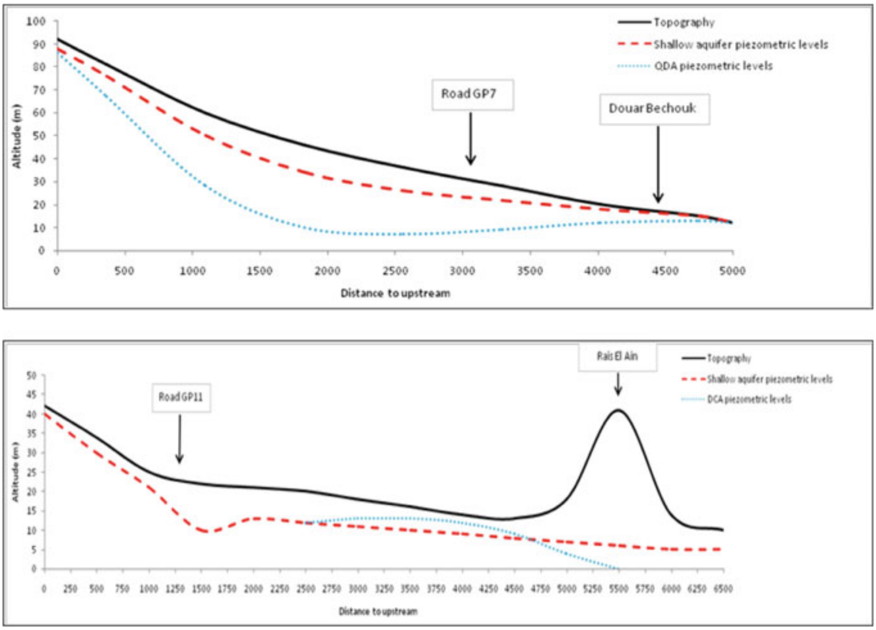

Fig. 9 Piezometric transects indicating the relationship between the shallow aquifer and the Quaternary Deep Aquifer (T1) and between the shallow aquifer and the Deep Campanian Aquifer (T2) (Chkir et al. 2020)

indicating that the fractured limestones of the Campanian aquifer are a naturel drain for shallow water what enhance the risk of contamination transfer.

3.4 Geochemical Processes Affecting Groundwater Quality

The chemical composition of groundwater is regulated by various factors such as atmospheric input, rock-water interaction, anthropogenic activities, and biogeochemical processes. The weathering of minerals generally exerts an important control on groundwater chemistry and generally dominates the concentration of the major cations (Ca, Mg, Na, K) [50]. Several authors had highlighted the importance of mineral weathered in different geological contexts such as sedimentary basins, crystalline rocks, arkosic bedrocks, volcanic bedrocks or sandy formations [3, 51–54]. Ion types and concentrations likely depend on geographical issues with high evaporite mineral dissolution in arid and semi-arid areas [55–57], granite mineral origin in volcanic bedrocks and sea intrusion influence in coastal aquifers [58]. Different methods and approaches are used to investigate the water–rock interaction mainly based on mass balance [59] and cross-analysis of ion concentrations for the identification of geochemical processes [60, 61]. Additionally, intense agricultural that placed a high demand on groundwater resources worldwide also directly or indirectly play a major role in regulating groundwater chemistry. Groundwater contamination by agriculture practices is commonly identified by high nitrate levels [62, 63]. Nitrate fluxes in groundwater depend on the interactions of hydrological, biological and geochemical factors [64–68].

3.4.1 Water Analyses

The statistical summary of water quality parameters in the Mateur Plain given in Table 2 shows large variation ranges and high standard deviation for most parameters and all water masses.

Such wide ranges for solutes concentrations suggest that multiple sources and/or complex hydrochemical processes take place insight the aquifer. The high nitrate concentrations in the study area reflect a possible degradation of groundwater due to anthropogenic contamination.

Temperatures of all the water samples are within the WHO [69] prescribed limit for drinking water. The temperature of spring waters, of groundwater from the Deep Quaternary Aquifer (DQA) and the Deep Campanian Aquifer (DCA) have means of respectively 18.1 °C, 18.3 °C and 17.9 °C. These values are of the same magnitude of the mean annual air temperature (18 °C) and indicate that these waters are not disconnected from the ambient environment. The mean temperature of surface waters is about 11.9 °C and rather reflects the temperature of the period during which the sampling has been carried out (March). On the other hand, shallow groundwaters show a mean of about 16.1 °C indicating that the aquifer is likely influenced by cold winter precipitations.

Concentrations and chemical forms of many inorganic and organic solutes in groundwater are mainly controled by pH values. Groundwaters of the Mateur Plain are near-neutral to alkaline, with a pH ranging between 6.8 and 8, showing an average value of 7.4. All of the groundwater sampled had their pH values inside the recommended range of 6.5–8.5 for potability [69]. Alkaline pHs are observed for surface water stored by the Joumine and Ghezala dams upslope the catchment.

Electrical conductivity (EC) is viewed as a valuable indicator of the amount of dissolved materials in water [2]. Potable water should have electrical conductivity within the WHO guide range of 750–2500 μS/cm. This is the case with most water samples. Surface, DQA and spring waters show EC means of respectively 765, 1242.9 and 1744 $\mu S.cm^{-1}$. Shallow aquifer has a wider range of EC (199.9 to 12,230 $\mu S.cm^{-1}$), with a mean of 2933.7 $\mu S.cm^{-1}$. Approximately, 1/3 of samples have EC higher than 2500 $\mu S.cm^{-1}$ and 2 samples higher than 10,000 $\mu S.cm^{-1}$. These two particular points are not included in the statistical summary of water analyses. The first point is the spring A3 located at the eastern point of the Jebel Ichkeul. The highest temperature (38.6 °C), the highest electrical conductivity (17,390 $\mu S.cm^{-1}$) and the most acid pH (6.72) revealed an anomaly that could be explained by the deep origin of waters. This thermal spring is locally used for public bathing. The second point is the Lake Ichkeul which water parameters are largely

Table 2 Statistical summary of water chemistry parameters for the Plain of Mateur

Water entities		T °C	EC µS.cm^{-1}	pH	Dissolved ions (mg.l^{-1})								
					Cl^-	NO_3^-	SO_4^{2-}	HCO_3^-	Na^+	K^+	Mg^{2+}	Ca_2^+	Sr^{2+}
Springs	Min.	15.7	1379.0	6.7	145.3	0.0	98.0	262.3	84.8	0.0	23.5	125.6	0.5
	Max.	38.6	17,390.0	7.5	5280.1	197.8	2458.1	390.4	3110.0	102.3	219.0	1092.9	6.3
	Mean	22.2	4873.2	7.2	1289.2	76.8	643.8	337.9	766.1	24.2	69.8	361.7	2.2
	SD*	8.3	6270.1	0.3	1999.4	68.8	911.8	42.5	1174.5	39.2	74.9	366.8	2.2
Surface waters	Min.	10.6	633.0	7.4	48.8	12.9	91.8	183.0	41.3	2.8	14.4	84.7	0.8
	Max.	23.4	10,350.0	8.0	5871.2	42.6	2270.5	298.9	3352.6	129.8	300.6	894.5	5.5
	Mean	14.8	3161.3	7.8	1520.5	23.3	661.0	221.1	877.7	35.1	87.9	291.3	2.0
	SD*	5.1	4152.2	0.2	2512.0	11.8	929.9	45.7	1429.0	54.7	122.9	348.3	2.0
Shallow Aquifer	Min.	12.9	199.9	7.0	112.8	0.0	52.7	207.4	69.4	0.0	18.7	66.6	0.4
	Max.	22.2	12,230.0	7.8	3723.7	954.6	2042.3	933.3	2106.8	284.0	286.2	838.3	7.1
	Mean	16.0	2887.8	7.5	671.3	128.8	310.9	355.8	384.1	29.7	57.1	232.8	1.9
	SD*	2.0	2368.0	0.2	732.4	186.6	365.2	127.7	394.7	57.9	50.5	156.8	1.7
DQA	Min.	14.2	907.0	7.0	96.4	0.0	30.5	219.6	72.1	0.0	15.7	12.5	0.1
	Max.	20.1	1602.0	7.9	303.0	154.1	210.8	433.1	148.8	36.2	48.1	180.3	1.3
	Mean	18.3	1242.9	7.4	186.1	63.6	80.6	314.9	108.9	5.6	24.7	131.6	0.7
	SD*	2.1	238.4	0.3	63.4	48.0	52.8	62.7	24.7	11.7	10.3	50.9	0.4
DCA	Min.	13.2	638.0	6.8	57.4	0.0	58.3	183.0	41.8	0.0	15.2	86.4	1.0
	Max.	21.4	8780.0	7.9	2254.2	98.7	383.6	1018.7	1653.4	30.3	112.3	401.9	7.1
	Mean	17.9	2682.2	7.3	585.9	46.2	216.9	368.2	325.3	9.7	50.1	216.3	2.5
	SD*	2.5	2135.1	0.2	599.4	27.7	91.7	213.1	433.4	9.5	24.7	77.3	1.5

(continued)

Table 2 (continued)

Water entities		T °C	EC μS.cm^{-1}	pH	Dissolved ions (mg.l^{-1})								
					Cl^-	NO_3^-	SO_4^{2-}	HCO_3^-	Na^+	K^+	Mg^{2+}	Ca_2^+	Sr^{2+}
All waters	Min.	10.6	199.9	6.7	48.8	0.0	30.5	183.0	41.3	0.0	14.4	12.5	0.1
	Max.	38.6	17,390.0	8.0	5871.2	954.6	2458.1	1018.7	3352.6	284.0	300.6	1092.9	7.1
	Mean	17.0	2825.0	7.4	695.4	98.2	313.6	343.9	399.1	23.7	54.9	231.2	1.9
	SD*	3.7	2911.8	0.3	1062.7	151.4	462.6	137.1	612.1	49.1	55.7	187.8	1.7

*SD: Standard deviation; DQA; Deep Quaternary Aquifer; DCA: Deep Campanian Aquifer above surface waters range for the temperature (23.4 °C), the pH (7,37) and the EC (10,350 μS.cm^{-1}).

Chloride is often the most dominant ionic species in groundwater. It is highly mobile and not involved in common geochemical reactions that occur in aquifers [2, 69–71]. Chloride concentration can be used as an indicator for the anthropogenic contamination of groundwater because it is conservative in most of the natural environment and could originate from surface contamination sources [71–74]. Chloride concentrations range from 48.8 to 5871.2 mg.l^{-1} with a mean of 695.4 mg.l^{-1}. No health-based guideline value is proposed for chloride in drinking-water. However, chloride concentrations in excess of about 250 mg.l^{-1} can give rise to detectable taste in water [69]. On this basis, 45 of the 70 wells investigated can be regarded as contaminated. Higher concentrations are observed for the well P11 (3723.7 mg.l^{-1}), the spring A3 (5280.1 mg.l^{-1}) and the surface water ES1 (5871 mg.l^{-1}). Lowest values are observed for the borehole S4 (57.4 mg.l^{-1}), the spring A1 (145 mg.l^{-1}) and for the surface water ES3 (48.7 mg.l^{-1}).

Sulphate concentrations in shallow groundwater vary from 52.7 to 2042.3 mg.l^{-1}. High values are observed for wells P9 (690.2 mg.l^{-1}), P10 (696.9 mg.l^{-1}) and P11 (2042.3 mg.l^{-1}) located on the south side of the mountain of Jebel Ichkeul close to the Lake and in the swamp area during the dry season. Relatively high sulphates concentrations are also observed for well P26 (1269.3 mg.l^{-1}) close to the river-bed of wadi Melah and well P14 (800.6 mg.l^{-1}) and P16 (708.0 mg.l^{-1}) on the southeastern part of the plain. Low values are observed for wells P1 and P2 (53.8 mg.l^{-1} and 72.1 mg.l^{-1}) located at the northern part of the plain close to the outlet of the wadi Douimis. Sulphates concentrations reveal that this element is rather influenced by local conditions than by a particular spatial trend.

Calcium concentrations vary between 66.6 and 700 mg.l^{-1} for shallow groundwater and between 86 to 401 mg.l^{-1} for deep groundwaters. Dam waters have lower values with a mean of 90 mg.l^{-1}. Higher values have been observed for the spring A3 (1092 mg.l^{-1}) and the Lake Ichkeul (894 mg.l^{-1}).

Strontium, an alkaline-earth element chemically similar to calcium and magnesium, occurs in trace quantities in all natural water. Sources of strontium in groundwater are generally the trace amounts of strontium present in rocks. The strontium bearing minerals celestite ($SrSO_4$) and strontianite ($SrCO_3$) may be disseminated in limestone and dolomite. Celestite is also associated with gypsum deposits [75]. Because strontium and calcium are chemically similar, strontium atoms may also be adsorbed on clay particles by ion exchange processes [76, 77] that may reduce strontium concentrations in groundwater found in clay-rich sediments.

Concentrations of dissolved Sr vary widely in the Mateur Plain waters, ranging from about 0.1 to 7.1 mg.l^{-1} (Table 2). This range is homogeneous for most water types except for the Deep Quaternary aquifer with concentrations less than about 1.3 mg.l^{-1}. Relatively high values are observed in the Deep Campanian Aquifer and for shallow groundwater sampled close to the Ras El Ain area where limestones outcrop. High values are also observed for the point A3 (6.3 mg.l^{-1}) and ES1 (5.5 mg.l^{-1}) in the high-salinity waters close to the Lake Ichkeul. The strontium content of most groundwater has a lower range than that of surface water. For the 60 ground-water samples analyzed, 40% contained less than 2 mg.l^{-1} of strontium.

Most samples reveal low concentrations of potassium what could be explained by the tendency of this element to be fixed by clay minerals and participate in the formation of secondary minerals [78].

3.4.2 Salinity Distribution

Salinity is recognised as one of the most widespread cause of groundwater degradation. It reduces water availability and uses. Using saline groundwater for irrigation decreases agricultural productivity and long-term sustainability of fertile agricultural lands. In this case study, groundwater salinity varies spatially within the basin-fill aquifers. Dissolved-solids concentrations in groundwater range from less than 500 mg.l^{-1} to more than 10,000 mg.l^{-1}. Lowest values are observed near basin margins where groundwater is recharged through nearby mountains and surface waters while highest values are observed in topographically low areas of the basin close to streams and brackish or saline lakes such as the Lake Ichkeul. In the shallow aquifer, groundwater salinity decreases following water flow direction (Fig. 10). A high salinity value (3.2 g.l^{-1}) observed for the well P36 located near Henchir Beni Daoud area, southern the plain, could be explained by the dissolution of Triassic and Miocene gypsum formation outcropping at the Jebel Beni Daoud.

At the central part of the plain, from the Felta area toward the Jebel El Assafir, meant northwestern to southeastern, salinity values remain relatively low (0.7 to 1.8 g.l^{-1}) and below WHO standard of drinking waters despite high exploitation rate. Higher salinity values (2 to 8.7 g.l^{-1}) observed north of the Ras El Ain hill are explained by two different phenomena. The first one is related to the contribution of the non-permanent wetland along the southern shore of the Lake Ichkeul to the salinization of the underlaying shallow aquifer. In fact, during the winter, high discharge of surrounding wadis to the Lake Ichkeul induce an increase of the lake level what makes the water flood over a part of the plain and a large swamp of ca. 30 km^2 area appears [79]. This phenomenon has an influence on the flow direction of the wadi Tinja between the Lake Ichkeul to the Lake Bizerte (Fig. 1). When the water level of the Lake Ichkeul increases during the wet season, water flows from the Lake Ichkeul to the Lake Bizerte. While, the flow is inversed during the dry season and high quantities of salts are therefore injected in the Lake Ichkeul, the Lake Bizerte being a coastal lake directly related to the Mediterranean Sea. This phenomenon is enhanced during the drying up of the swamp since salts that concentrated by evaporation in the soils are dissolved and leached to the shallow aquifer during the following dry season. The second phenomenon that contributes to the salinization of the shallow aquifer is related to the leaching during runoff of miocene gypsum formation outcropping at the Jebel Messeftine.

At the extreme northwestern part of the plain, shallow groundwater remains of low salinity although their vicinity to the Lake Ichkeul. This is due to the discharge of wadi Sejnane and wadi Douimiss that recharge the shallow aquifer and limit the

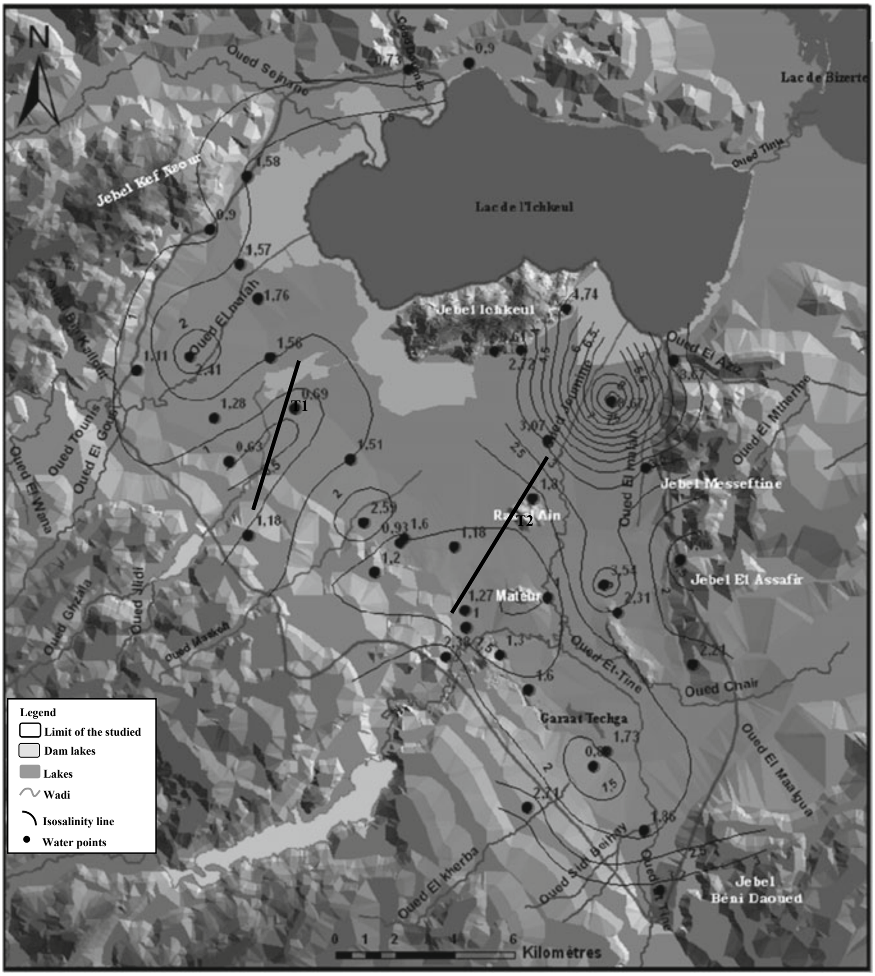

Fig. 10 Salinity map of the shallow aquifer (Chkir et al. 2020)

intrusion of the lake waters. However, although the high salinity of the wadi Melah, shallow groundwater adjacent to this wadi show low salinity values what confirm that the wadi is likely draining the shallow aquifer as shown by the piezometric map (Fig. 8). Some anomalies of salinity are observed in wells P6, P14 and P37. This has been explained by local leaching of saline soils reported for these wells. The salinity distribution of the shallow aquifer has been established without the well P11 which salinity value is too high (9.6 $g.l^{-1}$) compared to adjacent wells P9 and P10 with respectively 2.7 and 4.7 $g.l^{-1}$. This high salinity could be related to a local effect but also to a probable deeper level of the aquifer.

The salinity of the Deep Campanian Aquifer varies from 0.9 to 3.1 $g.l^{-1}$ increasing broadly north to south in the inverse direction of the water flow (Fig. 10). An important difference of salinity range is observed on the two sides of the hills Mateur and Ras el Ain. Salinity varies from 3.1 g.l^{-1} to 1.3 g.l^{-1} from eastern to western Mateur where the high permeability of the ancient delta cone of the wadi Joumine allows speed percolation of the shallow aquifer to the deeper one. The low residence time of groundwater limits water–rock interactions and therefore low salinities are observed. Salinity values of the Deep Quaternary Aquifer groundwater are homogeneous with a very low gradient toward the west from 0.5 to 1.2 g.l^{-1} (Fig. 11).

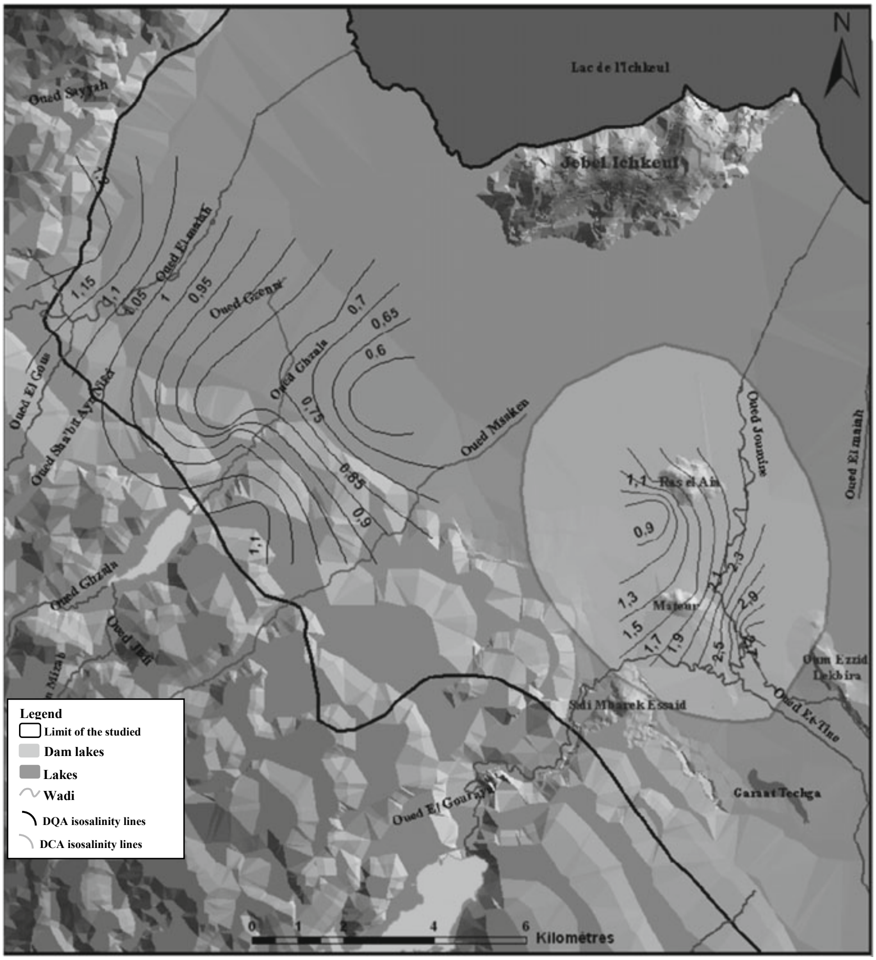

Fig. 11 Salinity map of the Deep Quaternary Aquifer (left black lines left) and of the Deep Campanian Aquifer (right red lines) (Chkir et al. 2020)

3.4.3 Water–Rock Interactions

The mineralization of groundwater is controlled by the geochemical processes taking place within the aquifer system. Major elements in groundwater are derived from solute concentrations in the precipitation, water–rock interactions in the soil zone above the water table and mineral reactions in the saturated zone below the water table. The evolution of chemical reactions along flow paths can, therefore, be determined by the observation of changes relative element ratios or in absolute concentrations from their initial compositions in the outcrop. In most cases, groundwater movement downflow paths follows a sequence of geochemical reactions that may provide information on chemical maturity and relative residence times of the groundwater [80–83]. The classification of water solutions in hydrogeological systems is often determined with the application of the concept of hydrochemical facies which enables a convenient subdivision of water compositions by identifiable categories and reflects the effect of chemical processes occurring between the minerals within the subsurface rock units and the groundwater [2, 84, 85]. The relative ionic composition of groundwater samples collected from springs, wells and boreholes in the study area are plotted on Piper trilinear diagrams [84]. Hydrochemical facies for the study area shows that there are two types of water, Ca-Cl and Na-Cl type, with variable concentrations of major ions. The distribution of groundwater facies over the plain is independent of their location. Each type could be found on the margin of the basin or in its central part. This means that groundwater in the area is mainly made up of mixtures of earth alkaline and alkaline metals and predominantly Cl water type. The Na-Cl type is observed for the spring A1 situated at the N-W part of the basin and the Lake Ichkeul waters, also influenced by NO_3. Two points also exhibit clear Na-Cl type, S8 and S13, respectively from the Deep Quaternary Aquifer and the Deep Campanian Aquifer.

Groundwater mineralization of the Mateur Plain is mainly controlled by Cl^- and SO_4^{2-} for anions and Ca^{2+}, Na^+ and Mg^{2+} for cations. Bicarbonates present considerable contents for most groundwater samples and show two proportional trends with TDS. This is also the case for strontium contents (Fig. 12). These relationships indicate that halite (NaCl) and gypsum ($CaSO_4.2H_2O$) dissolution, as well as calcite ($CaCO_3$) and dolomite $CaMg(CO_3)_2$ weathering, are the major sources of dissolved ions. On the other side, points plotted between two poles represented by the fresh recharging water of Joumine dam (ES2; ES3) and the saline water of the Lake Ichkeul (ES1) (Fig. 12) what indicate that a mixing process is also contributing to the groundwater mineralization.

Molar ions relationships including Na^+-Cl^-, Ca^{2+}-SO_4^{2-}, Ca^{2+}-Mg^{2+} and $Ca^{2+} + Mg^{2+}$-$HCO_3^- + SO_4^{2-}$ have been used to identify the minerals of source rock types and to evaluate the intrusion of brackish water from the Lake Ichkeul. The relationship between Na^+-Cl^- is commonly used to identify the process that controls the salinity and saline intrusion in arid and semiarid areas [2, 5]. The origin of sodium concentration can be from different processes in the groundwater but mainly from evaporite dissolution and in particular halite dissolution. The availability of free halite for dissolution in the soil zone may increase in the arid and semiarid regions with low

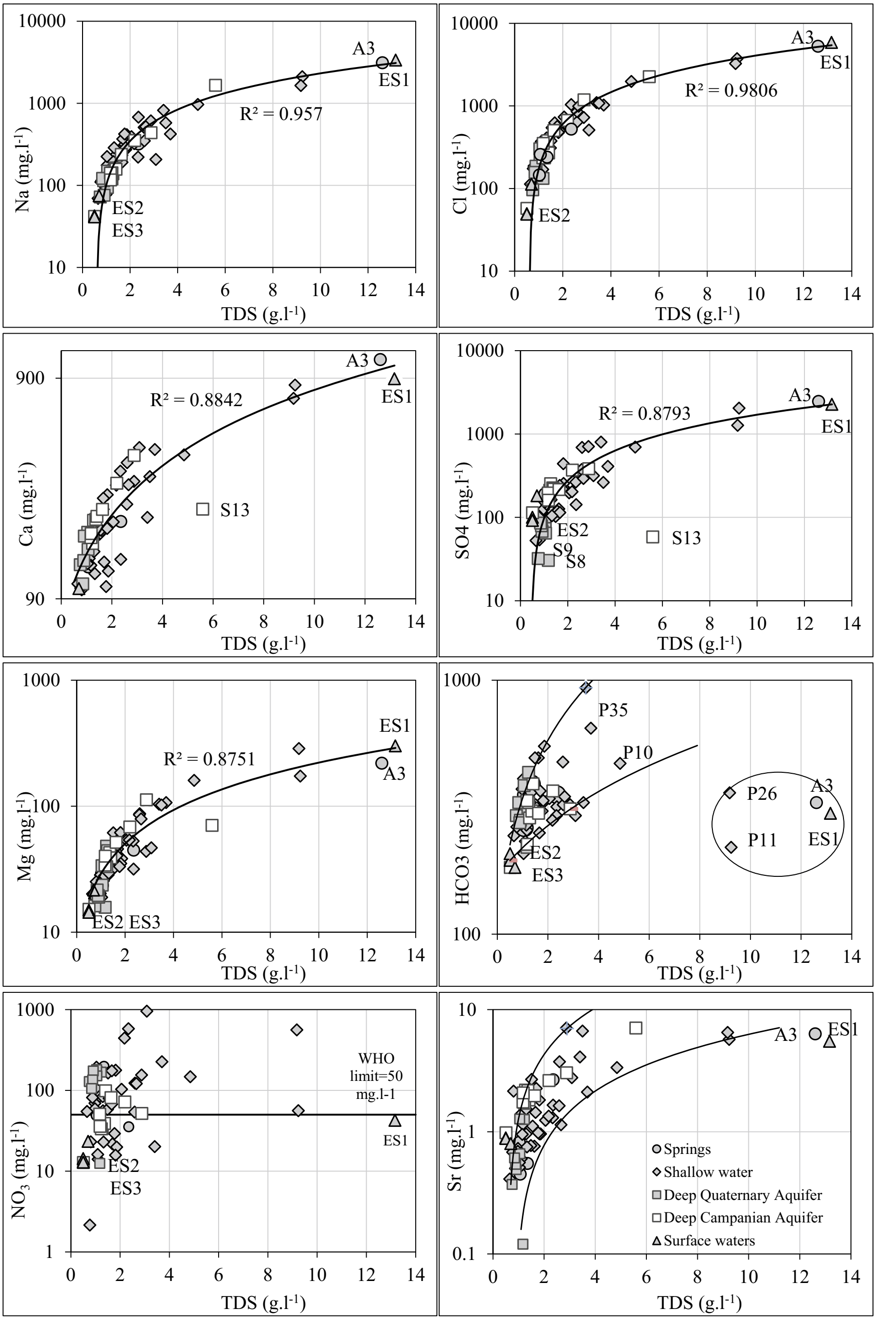

Fig. 12 Relationship between TDS and dissolved ions concentrations (mg.l^{-1}) in the Mateur Plain groundwater (y-axis are presented log-axis to cover large ranges). (Chkir et al. 2020)

annual precipitation of less than <600 mm. Generally, when halite dissolution is the dominant process of mineralization, Na^+ *vs* Cl^- relationship gives 1:1 ratio. Figure 13 indicates that 35% of the samples plotted along the equiline probably derived from the dissolution of disseminated halite in fine-grained sediments as observed in the basin. 43% of samples are affected by a deficit in Na and 22% by an excess of Na. All spring waters reveal halite dissolution while surface waters are enriched in Na^+ that may represent sodium which had been released from the silicate weathering process. Except for the Lake Ichkeul waters that are enriched in Cl^- probably in relation with the intrusion of the coastal Bizerte lake waters. Excess of Na^+ in groundwater could be explained by ion exchange.

Several sources of sulphate exist in the aquifer. The most apparent source is the dissolution of evaporite minerals (gypsum and anhydrite). Trace evaporites have been observed in well cuttings or cores in shallow parts of the aquifer. Saltwater mixing could also be a source of sulphate in inland areas. Other possible sources include oxidation of sulphide minerals, such as pyrite, or diffusion of sulphate from clays in overlying beds. Surface sources of sulphate include meteoric rainwater that contains sulphate, oxidation of organic sulphur, and anthropogenic sources such as fertilizers applied in the form of sulphate salts.

The scatter plots diagram for Ca^{2+} *vs* $SO4^{2-}$ (Fig. 13) indicates that most points (88%) plotted above the equiline 1:1 without any correlation trend indicating that these ions have different sources. Samples plotted along the equiline are located close to the Jebel Ichkeul (A3, ES1, P10) where Triassic salted formations outcrop. Only one sample plotted below the equiline indicating different sources of sulphate other than gypsum dissolution.

Calcium and magnesium were the dominant cations in wide areas of the basin. Carbonate rock weathering or silicate rock dissolution can be proposed as the primary process of Ca^{2+} enrichment for shallow and deep groundwater. The abundance of Ca^{2+} and Mg^{2+} could be related to the weathering of carbonate rock in the basin as shown by the groundwater's Ca^{2+} *vs* Mg^{2+} diagram (Fig. 13). Samples plotted along the equiline are affected by the dissolution of dolomite rocks while those plotted above this line indicated a more dominant calcite contribution from the rocks [86]. On the other hand, Ca^{2+}/Mg^{2+} ratios greater than 2, samples plotted above the equiline 2:1, may represent the dissolution of silicate minerals into the groundwater [87]. Only a few samples (17%) of the groundwater samples plotted between the equiline 1:1 and 2:1 which indicated that the dissolution of calcite could also be a process of Ca^{2+} and HCO_3^- enrichment of these samples [86–89]. These samples are mostly from the shallow aquifer at the central part of the basin. 81% of groundwater plotted above the equiline 2:1 which showed that silicate weathering dominates over carbonate dissolution in the groundwater calcium and magnesium concentrations [83]. Only one sample (S8) is indicative of the dissolution of dolomite with Ca^{2+}/Mg^{2+} ratio < 1.

"The dissolution of carbonate minerals could be represented in the following reactions" [89] from (1 to 4) in natural systems:

$$CaCO_3(Calcite) + H_2CO_3 \rightarrow Ca^{2+} + 2HCO_3^- \tag{1}$$

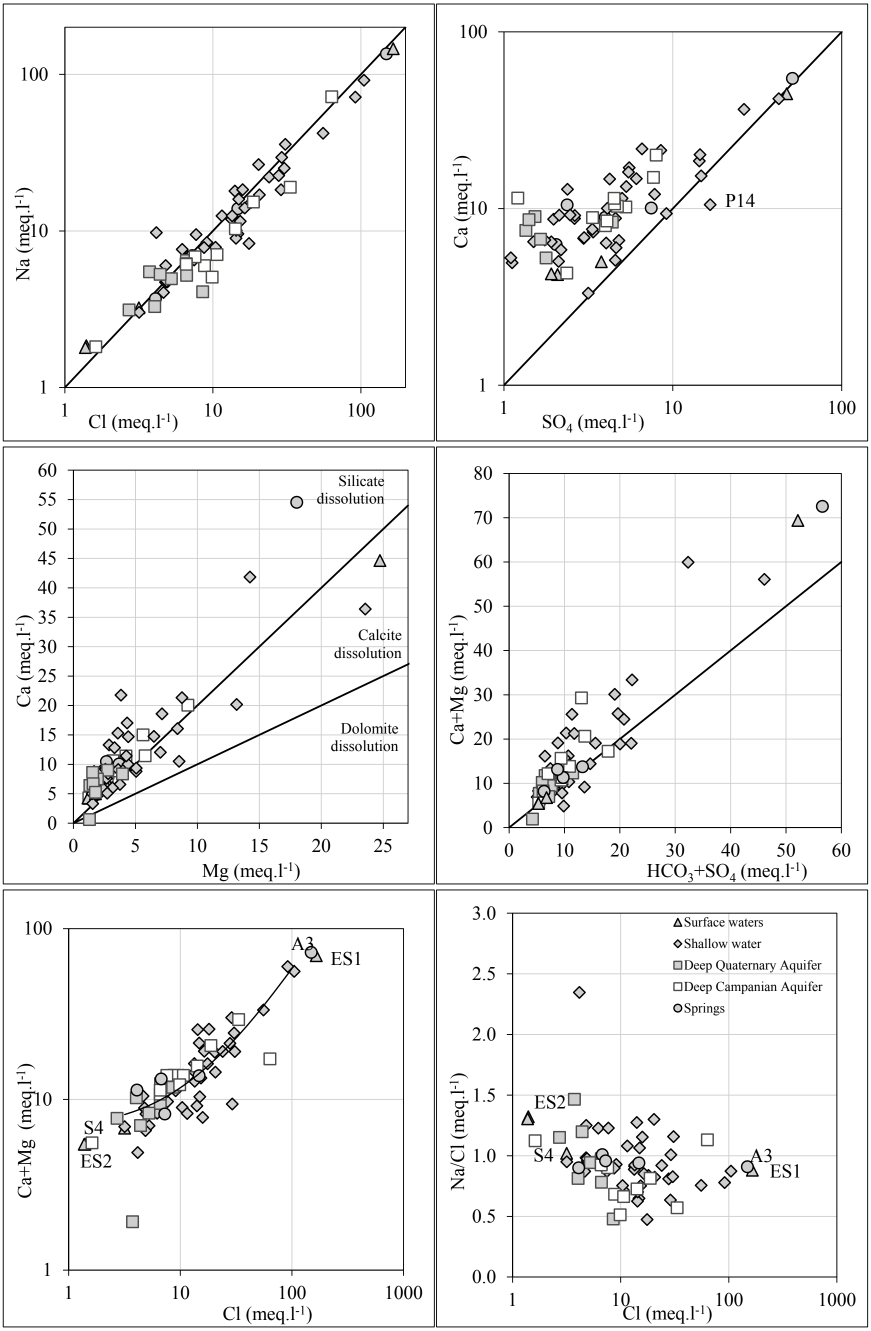

Fig. 13 Ions relationships for water–rock interaction differentiation (Chkir et al. 2020)

$$CaMg(CO_3)_2(Dolomite) + H_2CO_3 \rightarrow Ca^{2+} + Mg^{2+} + 4HCO_3^- \quad (2)$$

$$CaCO_3 + H_2SO_4 \rightarrow Ca^{2+} + SO_4^{2-} + H_2CO_3 \quad (3)$$

$$CaMg(CO_3)_2 + 2H_2SO_4 \rightarrow Ca^{2+} + Mg^{2+} + 2SO_4^{2-} + 2H_2CO_3 \quad (4)$$

The plot of Ca^{2+} + Mg^{2+} *vs* HCO_3^- + SO_4^{2-} will be near to 1:1 line if Ca^{2+}, Mg^{2+}, SO_4^{2-}, and HCO_3^- are derived from the dissolution of calcite, dolomite, and gypsum. If ion exchange is the dominant process, the data points tend to shift to the right due to excess of SO_4^{2-} + HCO_3^-. While, if the points are above the median line, reverse ion exchange is the active reaction for the excess of Ca^{2+} + Mg^{2+} over SO_4^{2-} + HCO_3^- [89]. The average ratio of Ca^{2+} + Mg^{2+}/HCO_3^- + SO_4^{2-} was 1.32. Based on the plot (Fig. 13), 40% of samples were scattered close to the 1:1 line, indicating that Ca^{2+} and Mg^{2+} in the groundwater are due to the dissolution of calcite, dolomite, and gypsum. This corresponds to the known lithology of the drained basin, essentially made by carbonated and evaporitic formations. However, more than 55% of the samples fall above the median line, indicating that the reverse ion exchange tended to be the dominant reaction over ion exchange. Ions exchange process can occur when water is in contact with some minerals such as clay minerals (kaolinite, montmorillonite), zeolitic minerals, ferric hydroxydes and organic material (humus) [90].

The plot of Ca^{2+} + Mg^{2+} vs Cl^- and Na^+/Cl^- *vs* Cl^- clearly indicated that the salinity increased with an increase in Ca^{2+} + Mg^{2+}, which also may be due to reverse ion exchange in the clay/weathered layer (Fig. 13). Molar Na^+/Cl^- ratios show a broad decrease as salinity increases indicating that other processes are also contributing to mineralization of groundwater.

Strontium-calcium ratios were calculated for all samples in which both ions were determined. The ratios ranged from 72 to 1048. Calculation of an average Ca^{2+}/Sr^{2+} ratio has little significance because of the variability among the samples and the great irregularity in the distribution of the sampling sites. However, it may be pointed out that the Ca^{2+}/Sr^{2+} ratios in groundwater sampled from the Deep Campanian aquifer are relatively low, one sample (S8) of which also had an unusually low Ca^{2+}/Sr^{2+} ratio (32) that probably reflected the local lithology. Strong geochemical affinities between Sr^{2+} and Ca^{2+} result in a moderately well-defined correlation of concentrations in shallow and deep groundwater samples (Fig. 13), indicating a more or less uniform source of alkali-earth elements over a large area in these aquifers. Ca^{2+}/Sr^{2+} and SO_4^{2-}/Cl^- ratios are used to refine the geochemical characterization of groundwater-surface water interaction. The divalent cation ratio Ca^{2+}/Sr^{2+} furnishes information regarding solute sources such as silicate weathering versus carbonate weathering and the mixed-valence ratio SO_4^{2-}/Cl^- provides information pertaining to the presence and type of evaporites (gypsum versus halite). Combining these differences, anion and cation ratios of these elements can serve to distinguish aquifer geochemistry (Fig. 14). High SO_4^{2-}/Cl^- values, indicating a dominant evaporite

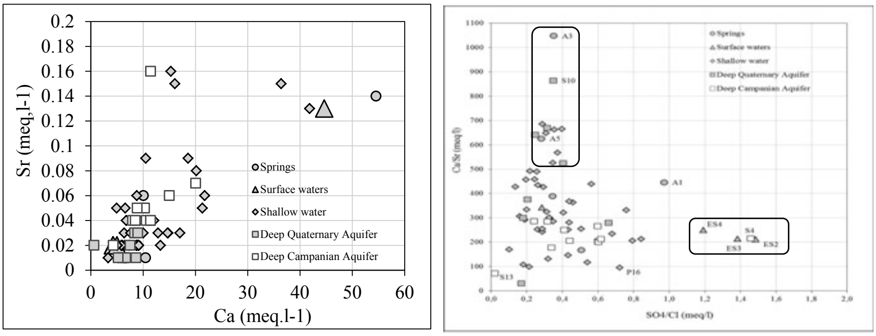

Fig. 14 Strontium-Calcium as indicators of geochemical processes in waters (Chkir et al. 2020)

dissolution mineralization process, are observed in samples ES2, ES3, ES4 and S4, respectively from Joumine dam, Ghezala dam and a neighboring Deep Quaternary aquifer point. These waters have flowed through Triassic outcrop before recharging the aquifer system. High values of Ca^{2+}/Sr^{2+} ratios as observed in the A3 point emerging in the Jebel Ichkeul, reflect the readily soluble alkali-earth elements from soil carbonate. Ion exchange between alkali-earth elements of water and aquifer rock surfaces is an effective means of removing both Ca^{2+} and Sr^{2+} from solution but will not cause large fractionation between the two geochemically similar elements so that base exchange previous identified by Ca concentrations are not apparent in this diagram.

The saturation state of the groundwater was reviewed with respect to the major carbonate minerals in order to investigate the thermodynamic controls on the composition of the groundwater and the approximate degree to which the groundwater has equilibrated with the various carbonate mineral phase. The saturation indices indicate that shallow groundwaters are undersaturated with respect to calcite, anhydrite, dolomite, gypsum and halite. Whereas, Deep Campanian and Quaternary groundwaters are saturated with respect to calcite, aragonite, dolomite and undersaturated with respect to anhydrite, gypsum and halite (Fig. 15).

3.4.4 Effect of Land Use on Groundwater Chemistry

Nitrate is the most ubiquitous contaminant of groundwater resources. It may derive from a number of natural and anthropogenic sources including intrinsic geologic origins, application of synthetic fertilizers and animal manure, leakage from defective septic tanks, discharges of wastewater and biosolids from wastewater treatment plants and industrial food processors, atmospheric deposition of nitrogen pollution, and the over-cultivation of nitrogen-fixing crops. However, despite the multitude of potential sources, it is the extensive use of agricultural fertilizers in intensive food production that has incomparably led to nitrate contamination of groundwater [63–65].

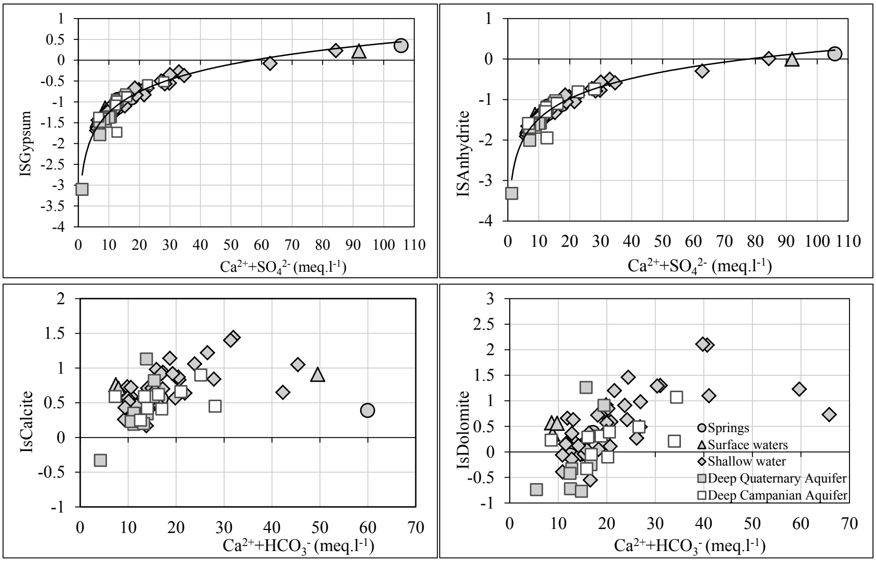

Fig. 15 Saturation indices for carbonate and evaporite minerals (Chkir et al. 2020)

Nitrogen fertilizers often applied to cultivated soils in exceedance of crop requirements, escape through the soil profile and move through the intermediate vadose zone to the underlying aquifers [65]. Consequently, soluble nitrate may concentrate to levels that create a public health risk to populations that procure drinking water from groundwater wells. As mentioned earlier, the groundwater is the sole source for domestic and agricultural activities in the study region. Further, cultivation of paddy and grams are economically important in the study region, and most of the basin is covered by agricultural lands and residents. Hence, groundwater contamination by irrigation return flow and fertilizer application, leaching of soil mineralized nitrogen and domestic sewage is highly expected in the study area. Nitrate concentrations range from 0 to 954.6 mg.l^{-1} with a mean of 98.2 mg.l^{-1} (Table 2). More than fifty percent of the 70 samples showed nitrate concentrations exceeding the WHO drinking water standard (50 mg.l^{-1}) and reveal that some of the well water is significantly affected by anthropogenic inputs [63, 64, 91]. The not proportional concentrations of nitrates with regard to the TDS suggest that the contamination of waters by this element remains restricted to some local issues. Higher concentrations are observed for points P17, P12, P37 (respectively 954.6, 572.3, 560.3 mg.l^{-1}). These shallow groundwaters have been collected from wells used for intensive farming and livestock watering without any protection against polluted seepage. This contamination is enhanced by coarse-textured soils and by low water table depth. In the southern part of the basin, nitrate concentrations are low because the vadose zone is very clay and the level of water is very deep [91–95]. The mixing of different NO_3^- sources can be characterized by the pattern of NO_3^-/Cl^- ratios and Cl^- concentrations. Agricultural inputs (high NO_3^-/Cl^- ratios and low Cl^- concentrations) are the dominant NO_3^- sources in the Mateur Plain, in particular in intensive farming areas such as Henchir Elkholjene south of the Jebel Ichkeul. Samples characterized by low NO_3^-/Cl^- ratios and high Cl^- concentrations are those collected from the Lake Ichkeul and surrounding wells (ES1, A3, P11, P26, P10) confirming a mixing between lake Cl-rich waters and groundwater. The Lake Ichkeul has very low NO_3^- contents indicating that although the long-term intensive farming of the area, the lake is not yet contaminated. Nitrate of surface water from dam storages and deep groundwater are both originated from natural sources (precipitation and soil organic nitrogen) with little influence of anthropogenic activities. These samples (ES2, ES3, ES4, S4) show low NO_3^-/Cl^- ratios and Cl^- concentrations. Some samples (A3, S8, P40) have no nitrate contents or at least under limit detection indicating that nitrate contamination still remains related to local issues (Fig. 16).

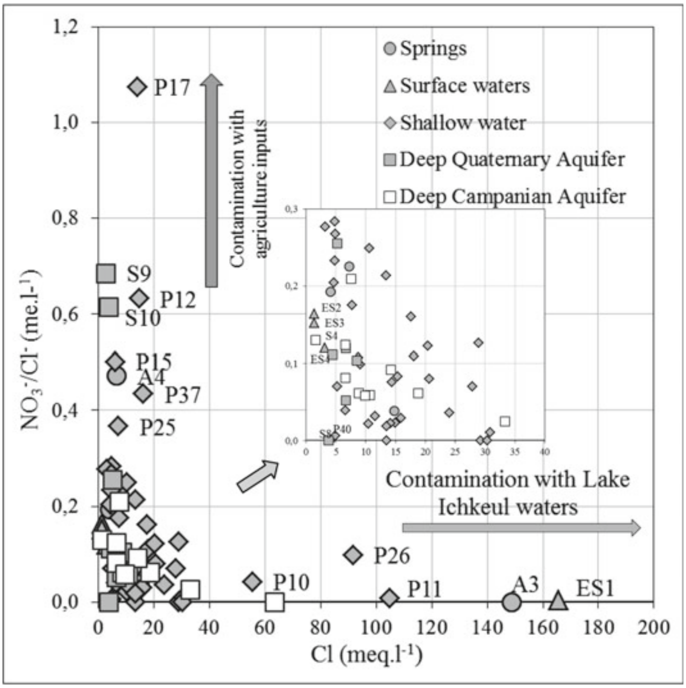

Fig. 16 NO_3^-/Cl^- ratios *vs* Cl^- concentrations (Chkir et al. 2020)

Table 3 Stable isotopes fingerprints of different water of the Plain of Mateur

Water masses	‰ VSMOW	
	^{18}O	^{2}H
Shallow aquifer	−5,25 ± 0.53	−32,7 ± 2.7
Deep Quaternary Aquifer (DQA)	−5,54 ± 0.42	−34,3 ± 1.5
Deep Campanian Aquifer (DCA)	−5,51 ± 0.32	−33,1 ± 2.5
Springs	−5,62 ± 0.38	−34,1 ± 2.4
Dam storage	−4.95 ± 0.51	−29,3 ± 3.9
Lake Ichkeul	−4,47 ± 0.10	−24,6 ± 1.1

3.5 Groundwater Residence Time as Inferred by Isotopic Tracers

Stable isotopes recorded for a variety of locations across the site indicate several water origins. Although the limited area (250 km^2) and the low altitude (60 m of height difference) of the Mateur Plain, samples revealed a large range of variation for oxygen 18 and deuterium, respectively 2.88 ‰ and 14.66 ‰ VSWOM. Stable isotopes contents vary between −6.16 and −3.28 ‰ VSMOW for oxygen 18 and between −23.23 and −37.75 ‰ VSMOW for deuterium with a respective mean of −5.25 and −31.63 ‰ VSMOW. Mean values calculated for each water type (surface water, Joumine and Ghezala dams storage, Lake Ichkeul, springs, shallow aquifer, deep Quaternary and Deep Campanian aquifers) are quite homogeneous (Table 3).

Waters from the Campanian Deep Aquifer collected close to Mateur, and Ras el Ain areas are characterized by δ^{18}O ranging between −4.8 and −5.9‰ VSMOW and by δ^{2}H ranging between −30.3 and −37.4 ‰ VSMOW, no particular spatial pattern could be noticed. Only one sample situated directly downstream the Ras El Ain Hill is affected by isotopic enrichment (S16b). Deep Quaternary Aquifer groundwaters show δ^{18}O ranging between −4.8 and −6.2‰ VSMOW and by δ^{2}H ranging between −32.4 and −36.4 ‰ VSMOW with an enrichment trend toward the southeastern (S8:-4.8 ‰ VSMOW) in relation with the flow path.

Data are plotted on the δ^{2}H *vs* δ^{18}O diagram together with the Global Meteoric Water Line (GMWL: $\delta^{2}H = 8\delta^{18}O + 10$; [35, 36]), the Local Meteoric Water Line (LMWL: $\delta^{2}H = 8\delta^{18}O + 12.4$; [92]). The mean weighted composition of local recent rainfall as recorded at Tunis-Carthage station, the nearest IAEA station, is also plotted on the diagram (Fig. 17).

Surface waters are represented by one point for Lake Ichkeul, twice for Joumine dam and one for Ghezala dam. Although a weak enrichment, these points plot close to the GMWL. Since the sampling had been carried out during the autumn, stable isotope contents seem to be influenced by precipitations entering the lake and dam storages. Detailed long-term monitoring could help to refine the budget of these water entities but is not concerned by this study.

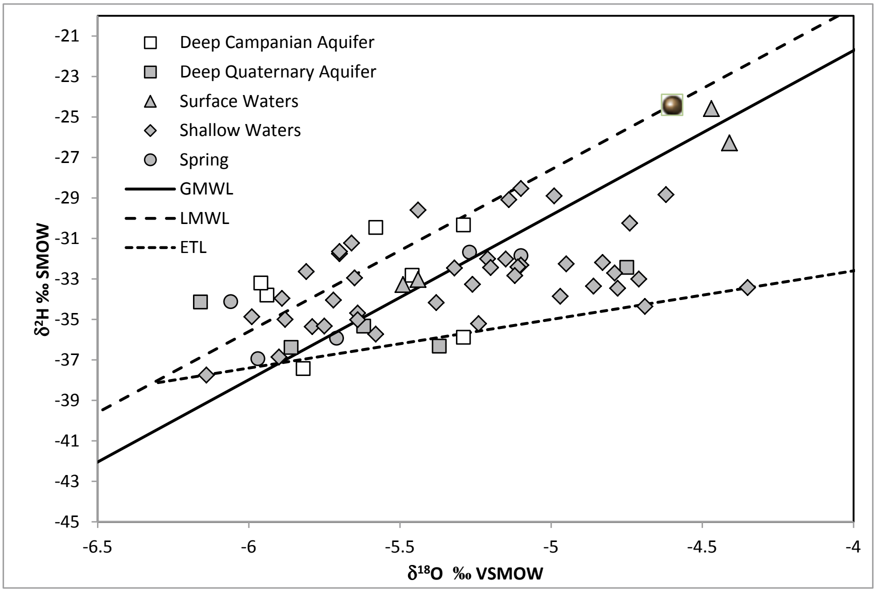

Fig. 17 Stable isotope δ^2H *vs* δ^{18}O diagram for the Plain of Mateur waters (Chkir et al. 2020)

The δ^2H and δ^{18}O values of the groundwater samples lie closely around meteoric water lines indicating that the groundwater most probably comes from present-day precipitation, though with a significant shift to the right of the LMWL. Scattering of the points between the two references lines shows that Atlantic, as well as Mediterranean vapor masses, could contribute to the precipitation events that ensure the recharge of this aquifer. Variations in the isotopic composition of precipitation, related mainly to temperature-dependent effects during condensation of atmospheric vapour and air-mass history, result in systematic seasonal shifts along the meteoric water line oscillating between enriched summer rain and depleted winter rain [39, 40]. Waters that plot above the lines indicate that re-evaporation of precipitated water under low-humidity is occurring and that such re-condensed vapor is significantly contributing to local rainwater. This vapor mixture is often observed in open water surfaces areas [10, 42, 96–98] and could be related to the proximity of the Lake Ichkeul and the Lake Bizerte.

Waters that have undergone evaporation usually display systematic enrichment in both ^{18}O and deuterium resulting in a divergence from the MWL along evaporation lines having slopes ranging between 2 and 5, depending on the relative humidity. Evaporation could occur during the percolation through the soil, during water retention in lakes and reservoirs, during overland flow in arid landscapes before infiltration, or from near-surface water table after infiltration. Enrichment in heavy isotopes by irrigation-return flow is possible as well. A Local Evaporation Line (LEL) with a slope around 2.6 limits the spread of shallow waters. The relative displacement of points between the LMWL and the LEL indicates an influence on evaporation rates of varying local climate conditions (temperature, humidity, wind speed, etc.) and local aquifer parameters (water depth, soil lithology) naturally integrated over the evaporation season. The interception between the LEL and the LMWL provides an estimate of the weighted mean isotopic composition of annual rainwater in the basin of about −6.6 for oxygen 18 and −40.5 for deuterium (‰ VSMOW). This value is slightly depleted compared to the weighted mean values for regional recent rainfall ($\delta^{18}O = -4.6$ and $\delta^{2}H = -24.30$‰). This depletion could be partially explained by the effect on the atmospheric temperature of higher altitudes than that of the regional GNIP station. An isotope depletion trend of $\delta^{18}O$ with an altitude of about ~ 0.28‰ per 100 m has been obtained by empirical relationships between elevation and the isotopic composition of precipitation and groundwater throughout the world [97, 98]. The recharge altitude of the system (~615 masl) as calculated on the basis of this altitudinal gradient is slightly below the elevation (~640 masl) of catchment where the aquifer outcrops and where surface waters flood before reaching the basin. This confirms that the altitude effect is one of the parameters affecting the isotopic composition of recharging water.

Shallow groundwaters that undergone evaporation are located northwestern the basin close to the riparian zone around the Lake Ichkeul. In this part of the basin, isotopic enrichment could be explained by direct evaporation effect on the limited shallow water table depth (0–3 m).

A significant shift of the "d-excess" parameter, defined as $\delta^{2}H - 8\delta^{18}O$ (‰), from the meteoric water lines intercepts (+10 and +12.4‰) is used to identify the relative magnitude of kinetic fractionation in different water masses [39, 99, 100]. The reported analytical uncertainty in oxygen-18 and deuterium measurements of respectively 0.1 ‰ and 1 ‰ give an estimated analytical uncertainty in d-excess of 1‰. Thus, d-excess values higher than 13 and lower than 9 could be discussed. The d-excess values are ranging from 6.5 to 14.5 in DCA, from 5.6 to 15.2 in DQA, from 9 to 11.2 in surface waters, from 1.4 to 14.1 in shallow groundwater and from 9 to 14.4 in spring water.

As the $\delta^{18}O$ increases, the d-excess in all the samples decreases gradually (Fig. 18). Highest d-excess values (13 to15.2‰) and depleted $\delta^{18}O$ (−6.2 to −5.5‰) are observed in groundwater situated along piedmonts with near-surface water table (less 1 m depth). These values are combined with relatively high tritium contents (2 to 4.5 UT). These waters are likely recharged during large amount rainfall events or/and by a recharge derived partly from water evaporated under conditions of low relative humidity as known for Mediterranean Sea region with precipitation deuterium excess values above 15‰ [98]. The observation suggests that recharge of this first group of waters is rapid as the precipitation signal is not transformed during percolation through the unsaturated zone. Waters of the majority of sampled sites with intermediate values of d-excess (9 to13‰) show a large range of $\delta^{18}O$ (−6.2 to −4.5‰) and tritium contents (2.6-4.1 UT) except for the A3 spring. This second group of waters sampled mainly at the western and northern part of the basin but with no particular spatial pattern indicate modern precipitation without significant influence of evaporation effect. The isotopic distinction between these two groups of waters suggests different recharge sources; an eastern air mass with a high d-excess value

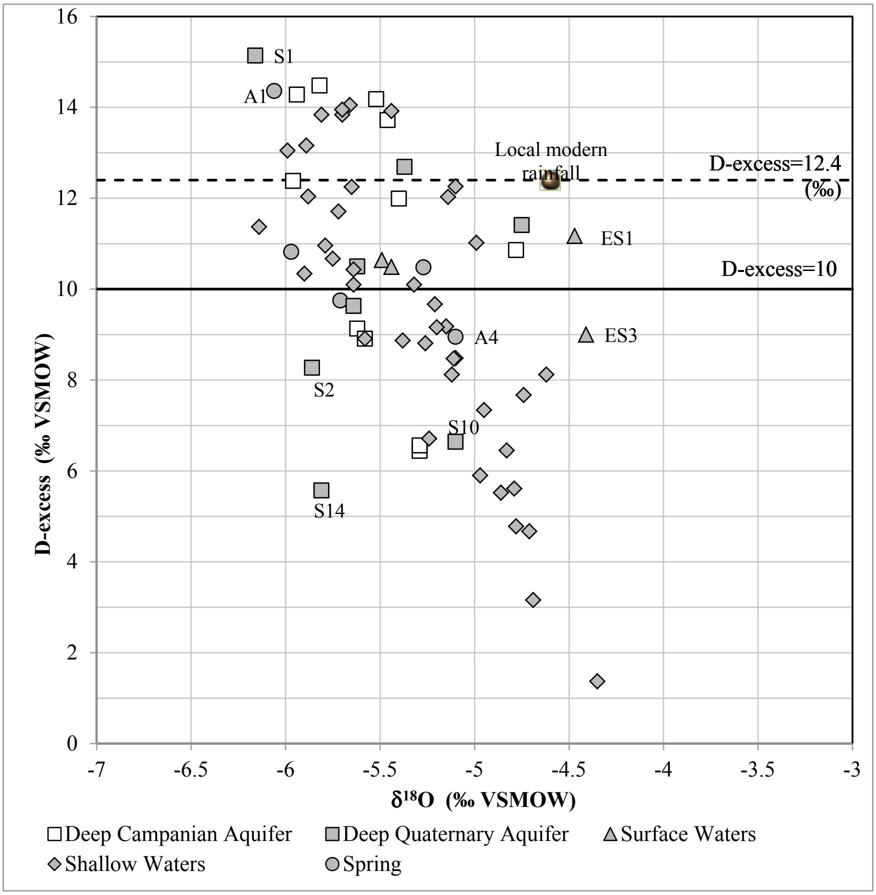

Fig. 18 D-excess *vs* $\delta^{18}O$ diagram for the Plain of Mateur waters (Chkir et al. 2020)

that affected the eastern part of the basin and a northwestern air mass that was the source for the recharge water upstream where are streaming the wadis discharging in the western part and the central part of the basin. It is proposed that the eastern air mass with a high d-excess value was derived from the Mediterranean [98]., whereas the northwestern air mass with a d-excess value similar to that of the global meteoric water line represents recharge under higher humidity conditions.

The second group includes all surface waters (dam storage and Lake Ichkeul) except the Ghezala dam (d-excess = 9) that seems to be more or less influenced by evaporation due to its limited depth and extension. The A3 spring located close to the Lake Ichkeul has the lowest tritium content of the basin (0.23 UT) which indicates a longer residence time or a mixing with older groundwater.

Groundwater which tends to have low d-excess values (<9) are affected by varying evaporation rates. These groundwaters are mainly sampled from the shallow aquifer in the central part of the basin. Lowest d-excess values (<4) are observed for points located in the variation field of the swamp area.

4 Conclusions

Water resources in the Mateur Plain have been investigated in order to assess natural and human constraints that control their potentialities. The shallow aquifer is lodged all around the basin in quaternary alluviums and is delimited by marls formations. Piezometric and isotopic data indicate that the recharge is ensured through the infiltration of precipitation mainly on bordering reliefs. The aquifer is mainly discharging in the fluctuating swamp around the Lake Ichkeul. In fact, water levels outcrop toward the lake around which an artesianism area appears during the wet season. Two deep aquifers have been delimited according to lodging formations. The first one is the Deep Quaternary Aquifer lodged in quaternary formations (DQA) and is mainly tapped in the western part of the basin. The second one is the Deep Campanian Aquifer (DCA) lodged in Campanian fractured limestones and restricted to Mateur and Ras el Ain areas. Piezometric mapping revealed hydrodynamic connections between shallow and deep groundwaters in particular between shallow and Deep Campanian aquifer that can be considered as a natural outlet of the shallow aquifer. All physicochemical parameters of these aquifers show very large variation ranges. Electrical conductivities vary between 907 and 17,390 $\mu S.cm^{-1}$ in relation with high dissolved salts contents (0.63–13 $g.l^{-1}$). The salinity of different waters is dominated by $Cl^- > Na^+ > Ca^{2+} > SO_4{}^{2-} > HCO_3{}^- >$ ions. Chemical facies are Ca–Cl and Na-Cl without any spatial distribution for groundwater as well as for surface water indicating mixing processes. Ionic ratios indicate that the water–rock interaction including dissolution of carbonate mineral and silicate weathering is the dominant process controlling the content of major ions in local groundwater. Dissolution of dolomite, calcite, and gypsum are the primary origins of major ions in groundwater as indicated by undersaturation of waters with respect to these saline minerals. The cation exchange reactions have significant effects on the levels of Ca^{2+}, Mg^{2+} and Na^+, especially in deep groundwater. The high heterogeneity of the aquifer is explained by the interference of several other parameters: i) leaching of saline soils during the infiltration of rainfall, ii) irrigation water return as indicated by high nitrates concentrations in intensive farming areas, iii) salt marshes extending downstream the plain around the Lake Ichkeul, and iv) outcrop lithology along surrounding mountains where surface waters are streaming before recharging the aquifer. Groundwater from the Deep Quaternary Aquifer is mainly of good quality (<1.2 $g.l^{-1}$). Those from the Deep Campanian Aquifer (0.5–5.6 $g.l^{-1}$) show an inverse gradient according to the flow path, salinity is decreasing downstream west of Mateur and near Ras el Ain area and is likely related to the higher permeability of the aquifer. On the other hand, oxygen 18 contents for different waters of the Mateur Plain (shallow aquifer, DQA, DCA, surface water, dam waters) are quite homogeneous ranging from −6.16 to −3.28‰ with an average of −5.25 ‰ VSMOW also indicating high mixing ratios between shallow and deep aquifers. Pre-recharge modification of the isotopic character of precipitated water caused by surface and atmospheric processes (evaporation, vapor recycling) as also the boundary conditions (proximity to large open surface water) are clearly identified in the isotopic composition of different water bodies. Stable water isotopes showed a direct relationship to local meteoric water, as well as evaporation effects. The main recharge in the local system is occurring all over the basin in alluvial deposits outcropping in the valleys and plateaus, infiltration along rivers and streams, and infiltration of excess irrigation in agricultural plots. Tritium analysis revealed the presence of modern groundwater and a relatively homogeneous recharge process. These results confirm that active recharge carries solutes into the subsurface under present conditions.

Water isotopes applied as a management tool helped to identify the origin of degradation risk of a multilayered aquifer situated in a high farming region. Both natural factors (limited recharge, the proximity of the coast) and human pressures (overexploitation, intensive farming) have created a low-level sustainability situation in relation to water resources availability.

Recommendations
The multitracer methodology combining geochemical and isotopic approaches could easily be used as a decision system tools for policy-relevant issues. The current investigation showed that even with a limited but spatially representative number of sampling points, reliable information are obtained on anthropogenic factors that reduces the water system sustainability. However, it's recommended to develop a long-term groundwater monitoring network for future improvement of the water resources management strategy.

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Assessing the Blue and Green Water Resources Use for Regional Crop Production in a Semi Arid Area (The Cap Bon Case Study, Tunisia)

Insaf Mekki and Rim Zitouna-Chebbi

Abstract Because of the strong expected effects of climate change on water resources and food production it is important to use efficiently, as well as sustainable, water for agriculture production including both components rainfed "green water" and irrigated "blue water". This is particularly important in the Cap Bon region northeastern Tunisia, where irrigation has increased in the past few decades, using intensively groundwater resources resulting in their degradation as well as their conflicting uses. Efficient management strategies that allow for compromises between agriculture production and water resource preservation are therefore needed. Such strategies require initial assessment of the sustainability of blue and green water resources management for crop production. For this purpose, the Global Water Footprint Standard approach has been used in the Cap Bon region. We calculated the volumetric blue and green water footprint related to wheat, tomato and citrus production as major crops in the region. The results show that the average of total WF of crop production was about 1821 Mm^3/yr (85% green, 15% blue) over the period 1999–2008. The total WF (green + blue) of tomato and citrus crops averaged 131 m^3/ton, 445 m^3/ton, respectively. The green WF of wheat obtained in this study was about 1670 m^3/ton, which is equal to the calculated world average (1620 m^3/ton) by previous studies. This indicates that large opportunities for improving water footprint are found in low yielding farming systems, particularly in rainfed agriculture (water productivity is already higher in irrigated agriculture because of better yields). The assessment of sustainability of water use showed that the crop growth period when tomato and citrus need water is basically the same as the no precipitation period. The irrigation water requirement furthermore corresponds to the period where the water scarcity is high.

Keywords Crop water use · Rainfed/irrigated agriculture · Water productivity · Agriculture production · Tunisia

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1 Introduction

Pressures on water resources have drastically increased in recent years due to human activities, the rapid changes in land use and the observed effects of climate change. Climate change projections [1] reveal that the Mediterranean region will be particularly affected by the drier and hotter conditions combined to the decrease of the renewable water resources to by up to 50% within the next 100 years. However, the extent and the accuracy remain imprecise, it is expected that climate change will result in a significant reduction in rainfall and an increase in the frequency of droughts. It is expected that water demand by 2030 is likely to exceed the conventional resources available. In Tunisia, agriculture represents 80% of all water abstraction in the country and 74% of the total consumption for the sector comes from groundwater [2] inducing aquifers overexploitation of 26% of them at an average rate of 146%. The efficient use of water for agriculture production will therefore be necessary to improve the productivity and ensure the better management of both components rainfed "green water" and irrigated "blue water". This nomenclature was introduced by [3], who in complement named as "green" water the part of precipitation that is stored initially in the unsaturated zone of the soil and lost by plant transpiration "productive" or soil evaporation unproductive. Both kinds of waters are important for sustainable farming systems. Green water is the main component of the water balance and is a basic resource for crop evapotranspiration in the semiarid areas [4]. It directly stems from the local infiltration of rainfall into the soil and, consequently, does almost not require any specific energy expense from the farmer. However, as estimated by [5], its average residence time is 5 months, which is not enough to allow for mitigating the effect of long dry periods. The blue water requires energy for its use as irrigation water. But, given its much larger residence time, 2.7 years on average after [5], it may be used to reallocate water from periods without or with small water shortage to periods with intense water scarcity, which helps to decrease the risk of complete crop failure. There is therefore a need to define and manage the best balance between green and blue water resources for sustainable farming systems. Land use is a major instrument through which blue and green water can be manipulated. It is known to largely influence the partition of rainfall into blue and green water [4]. The water footprint (WF) offers a useful tool to assess the use of water resources in crop production and can, therefore, support the prediction of the water consumption in rainfed and irrigated agriculture [6–10]. It is described as the volume of fresh water that is utilized during all process of crop production. WF accounting can be done at catchment, subnational, national, regional and global level, and it can be assessed from a consumer or producer perspective [11]. The bio-physical water productivity (WP, Kg/m^3) in crop production is in fact the inverse of the green–blue WF of crop production [9]. In order to grasp the effect of crop production on the sustainable use of water resources, facilitate decision-making processes, and to guide actions levers for better water management, the WF has been used [9, 10]. This is particularly important in the Cap Bon region northeastern Tunisia, where irrigation has increased in the past few decades, using intensively groundwater resources resulting in their degradation as well as their conflicting uses. Efficient management strategies that allow for compromises between agriculture production and water resource preservation are therefore needed. Such strategies require initial assessment of the sustainability of blue and green water resources management for crop production. For this purpose, the Global Water Footprint Standard approach has been used in the Cap Bon region in Tunisia to calculate the volumetric blue and green water footprint related to wheat, tomato and citrus production as major crops in the region.

2 Water Resources and Agriculture in the Cap Bon Region

2.1 Description of the Study Site

The study focuses on the Cap Bon region, it covers 2822 Km^2, located in the northeastern Tunisia (Fig. 1). The Cap Bon is a peninsula surrounded by the Mediterranean Sea on both sides. The Cap Bon landscape includes three zones (upstream, intermediate and downstream) according to geomorphologic, geological and land cover-land use criteria. A continuous ecosystem gradient is observed along the upstream–downstream transect. There are mainly three different soil groups: i) shallow, unstructured skeletal soils, poor in organic matter and sandy texture, ii) deep soils on alluvion in major river beds, silty-clay to clay-clay texture, moderately fertile, and iii) soils

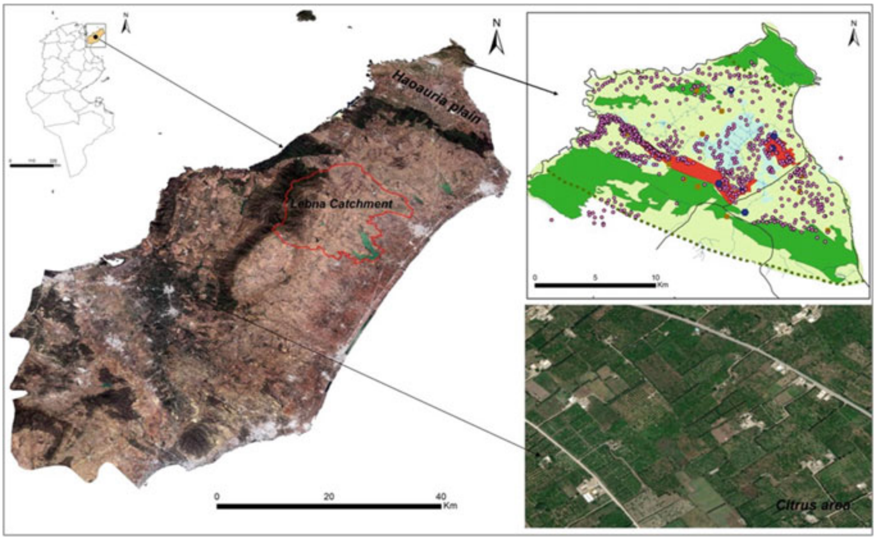

Fig. 1 The Cap Bon region northeastern Tunisia with its main dams, Lebna catchment (rainfed agriculture), the citrus area (irrigated from Madjerda Cap bon) and the Haouaria coastal irrigated plain from groundwater resources

representing all hills and plateau's. The depth of the soil varies from a few mm on the rocky outcrops and in the wadi beds to more than 2 m in the plains and on some accumulated slopes. The watersheds are subject to soil erosion and subsequent dam's reservoirs siltation.

Representing 4% of SAU of the country area, le Cap Bon participate with 14.3% of national agricultural production. The region has known an important development of the agricultural activities and tourism. The forest and the shrubs covers the mountainous areas. The natural vegetation areas include the steepest parts, as well as the shores of the hill reservoirs, lakes and wadis. One third of the agricultural area is devoted to arboriculture. The olive tree is the oldest species introduced to Cap Bon, and is found everywhere, grown in forest or in small numbers in intercropping plots. Vineyards and citrus orchards are intensively irrigated. In hilly catchments, agricultural systems are mainly based on rainfed mixed farming and livestock. As in other rainfed agricultural systems in North Africa [11], the rainfed agriculture mainly includes cereal production, although its climate increases the crop diversity. Annual crop areas spread over 30% of the area. The annual crops include grain cereals (mainly wheat), fodder crops (mainly barley, oats and triticale), spices (mainly coriander) and legumes (mainly fava bean). Agriculture suffers from fragmented and small-scale holdings. Within the Cap Bon region, the cultivated landscape consists of a mosaic of very small agricultural fields, and the average field area is less than 1 ha. Livestock husbandry includes cattle, sheep and goat breeding. The land of the plain with high agronomic potential allows the practice of intensive agriculture with vegetables and citrus. The Cap Bon region is a regional hotspot for potential trade-offs in green- and blue-water resources between upstream and downstream users. The use of irrigation remains important options for cropping patterns in the irrigated plains that have long consisted of traditional irrigated crops in rotation with fodder crops for livestock. An important portion of economic development is focused on the continuous increase of production for export of tomato and citrus. 85% of national citrus production is from the Cap Bon [14].

2.2 Characteristics of the Climate

The climate regime is between the Mediterranean upper subhumid and semiarid with a hot and dry summer and a mild and rainy winter season. The Fig. 2 shows the main average isohyets (mm/year), the annual rainfall at the Lebna and Kamech meteorological stations and the ombrothermic graph for two coastal zones. The mean annual rainfall and the mean annual evapotranspiration (Penman-Monteith reference crop evapotranspiration) range from 450 mm (averaged over 90 years at the nearest station meteorological located at Kelibia) to 800 mm and from 1000 to 1500 mm, respectively [12–14]. The long-term ombrothermic graph for the coastal zones shows near water deficiency conditions exist for the months of April–May to September–October. This indicates that crops grown during this season generally have an unfavorable water

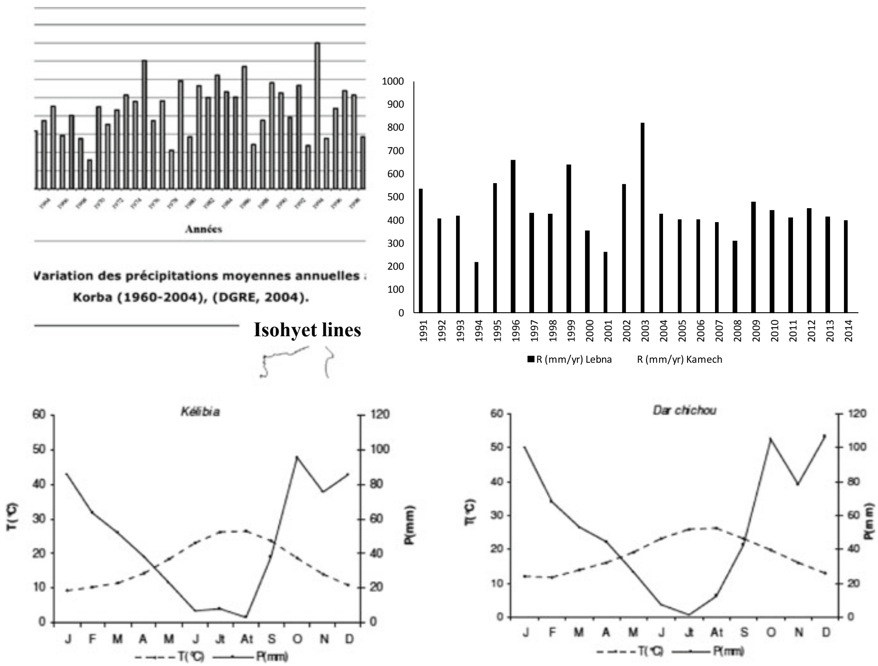

Fig. 2 The main average isohyets (mm/year), the annual rainfall at the Lebna and Kamech meteorological stations and the ombrothermic diagrams for two coastal meteorological stations in the Cap Bon region

and temperature relations during these months.Rainfall mainly occur from October to April while the main dry season lasts from May to September.

2.3 *Blue and Green Water Resources Situation*

The blue water supply for the Cap Bon region stems from groundwater and surface water resources in local dams, surface water transfer coming from the channel Medjerda-Cap-Bon in Northern Tunisia. The canal which transfers the northern water from several dams built on the Medjerda, the country's longest river, and allows their transport to several public irrigated areas of the region, located in the coastal areas. Groundwater, estimated at 260 Mm^3, originates from main six aquifers. They are marked by increasing pressure and persistent drawdown of water tables. For instance, in Haouaria plain aquifer, the increasing number of shallow wells led to significant groundwater abstraction and withdrawal rates of 60 Mm^3/year in the shallow aquifer, more than twice the natural recharge year, and high salinity levels (1.5–5 g/l with an average value of 3.2 g/l) observed in 2014 [14, 15]. Surface water is estimated at 150 Mm^3 of which 100 Mm^3 can be mobilized by important hydraulic infrastructure such as reservoirs and channels: 7 dams (mainly Lebna reservoir with capacity of storage of 30 Mm^3), 33 hilly dams and 53 hilly reservoirs (e.g. Kamech hill reservoir). From the water stored in these hydraulic infrastructures, the Regional Planning Commission for Agricultural Development (CRDA) of Nabeul has set up a program for the artificial recharge of the water tables during high water demand periods. Despite the strategies to mobilize water resources, the water scarcity continues to worsen. The reduction of surface water allocation to irrigated agriculture in order to meet the growing demand of competing uses (urbanization, industry and tourism activities) implies increasing irrigation pressures on ground water resources inducing their over-exploitation.

2.4 Characteristics of the Irrigated and Rainfed Agriculture

The Cap Bon region is one of the most productive agricultural area for irrigated exported crops (tomato and citrus) in Tunisia. Rainfed farming systems are predominantly based on food cereal, legume grains production and fodder crops for livestock. Intensive irrigation activities in this region have caused a substantial increase of groundwater extractions, and consequently the depletion of groundwater resources along with the degradation of their quality (salt intrusions, salinization of irrigated land). The sustainability of irrigated agriculture in the Cap-Bon region is questionable and decision makers are facing difficulties to manage and allocate the resources [15, 16]. Access to water resources is collective or private. Collective irrigation is based on the water management rules via water user associations that regulated water partitioning.

Tomato is the second most important commodity produced in terms of quantity by the country and it is grown annually on an averaged area of around 28,000 ha (30% in the Cap Bon region). The averaged total production in the Cap Bon area is about 400,000 tons (36% of the national production) in 2013. The average yield between 1991 and 2017 was 45 tons per hectare. The tomato has one main season which is all open field and runs from April till September. Citrus plantations cover an area of about 22,000 ha in 2018. Cap Bon remains the main production zone, accounting for almost 70% of total citrus farming area. The total area dedicated to oranges has increased over the last twenty years due to expansion of irrigated areas and also as a result of increased crop densities. The number of trees has increased by 26% since 1999 [14]. Rainfall is almost absent during the high evaporative demand period for citrus and the irrigation practices generally starts in April and stopped in December.

Wheat is one of the main agricultural productions at the base of the Tunisian food security as olives and tomatoes. Durum wheat is the most produced cereal [17], accounting for more than half of production (56.7%). In 2009, the harvested wheat area covered 53% of consumption requirements. The study of [18, 21] showed that the preceding crop is one of the important factors impacting significantly the maximum yield of wheat. The authors of the former study observed that the highest yield (5.8 t ha^{-1}) was obtained for wheat following legumes (excluding chickpea), followed by vegetables and chickpea and the lowest Ymax (3.5 t ha^{-1}) was found for wheat in cereal-wheat rotation.

3 Impact of Climate Change

Under the Representative Concentration Pathway (RCP), the projections indicate an increased risk of soil moisture drying in the Mediterranean, consistent with projected changes in the Hadley Circulation and increased surface temperatures, and surface drying in these regions is likely (high confidence) by the end of the century under RCP8.5 [1]. The study performed by [17] for Tunisia show a general increase in average temperature (average over the entire territory) between 1.6 and 1.9 °C in 2050 and between 2 and 3.9 °C in 2100 relative to the reference period. They also show for, RCP8.5, a general decrease in rainfall between −14 and −22 mm in 2050 and between −23 and −45 mm in 2100 relative to the reference period. The decrease trend is not significant for some local zones, seasons and for the RCP4.5 scenario.

3.1 Water Resources

The general decrease in rainfall, and the drought events will have an impact on the runoff and significantly decrease the inputs to dams by 5%. The increase in crop water requirements could lead to more exploitation of groundwater and the degradation of their quality. In addition, the rapid rise in sea level would also have a negative impact on the quality of coastal groundwater and might contribute to decrease their irrigation potential [17]. A prediction of 50% loss of current resources from the aquifers (nearly 150 million m^3) due to the increased sea level by 2030.

3.2 Irrigated and Rainfed Agriculture

Increasing water scarcity is the most pressing climate change impact (extension of dry periods and rising temperatures) on the agriculture production. Although the effects are unclear at local scale, the observed inter and intra-annual variability of temperature shortened the development cycle of crops. The water demand from irrigated agriculture will increase and competition between other different sectors will also increase. The availability of surface and groundwater resource will be affected by the higher costs of energy for pumping.

The study of [17] on rainfed cereal production under different climate change scenarios and varying rainfall, predicted a loss of rainfed production potential. Losses were estimated at 10%−20% of production area. The competing demands of the water between the different sectors (agriculture, industry, tourism and domestic consumers) will increase and, therefore generate tensions.

Different studies and authors claim that the difference in farm strategies, and consequently resilience to cope with climate change in the South Mediterranean area, can be explained by the diversities observed in terms of cultivated cropping systems (cereals vs. orchards; rain-fed vs. irrigated) [22, 31], types of farming systems(small farms vs. big farms; mixed farms vs. cereal farms) [31] and the availability and quality of water, land and labour resources [19, 31, 32]. Studies on the impact of climate change recommend a period of at least 20–30 years to have a significant change of the driving forces [25]. However, for such a long-time horizon, there is a strong uncertainty regarding the technical and socio-economic evolutions. For example, as far as the economic domain is concerned, the volatility of product prices and the evolution of agricultural policies are the main reasons for such uncertainty [19, 24].

3.3 Climate Change Adaptation

Rainfed agriculture has suffered from insufficient policy and institutional support for improving water management for production in changing climate. The focus over the past 50 years at the farm level has been mainly on soil conservation, and to a lesser extent in-situ water conservation (maximizing rainfall infiltration) through various strategies. Government programs in relation to water saving in irrigated agriculture are partially used to recover the investments in irrigation equipment. For catchment levels, policies have focused on remediating the negative effects of water upstream (erosion control and water conservation) to reduce the downstream impact. In recent decades, however, the focus has shifted from water management for conservation to water management for production upstream. Water harvesting, small irrigation and marginal water use can help improve water availability. Farmers' strategy for coping with climate change was to reduce the area of the less profitable irrigated winter forage which is then replaced by purchased hay and feed concentrates [19, 24].

4 Methodology and Used Data

The study adds to earlier studies of water footprint for Tunisia [8, 10] by addressing the regional dimension in a comprehensive national water footprint assessment.

As defined by [26], "the WF of a product is the volume of fresh water used to produce the product, measured over the full supply chain". The WF of a crop is generally expressed in terms of m^3/ton [26]. The water productivity (WP) is the inverse of the green–blue WF of crop production [9]. [23] defined the physical WP as "the ratio of agricultural output to the amount of water consumed". The water consumption is estimated from the blue water extraction or the total amount evapotranspiration from green and blue water.

4.1 Calculating Blue and Green Crop Water Use

[26] explain the water footprint of the process of growing a crop (WF) as the sum of the WF of the different sources of water following the Eq. (1):

$$WF(volume/mass) = WFblue + WFgreen \tag{1}$$

The blue (WF, blue, m^3/ton) and green (WF, green, m^3/ton) components of the water footprint were calculated as the amount of water supplies for irrigation and the effective rainfall (IWU, m^3/ha, ER, m^3/ha) divided by the crop yield (Y, ton/ha) following Eq. (2) and Eq. (3):

$$WFblue(m^3/ton) = IWU/Y \tag{2}$$

$$WFgreen\left(m^3/ton\right) = 10 \times Eff.R/Y \tag{3}$$

We consider the blue water (water supplied in crop production from the irrigation “IWU” from surface and groundwater sources). We consider the green water (water supplied in crop production from the effective rain “Eff.R” [27]. The factor 10 was used to convert effective rain water depths in millimeters into water volumes per land surface in m^3/ha.

We divided the amount of crop production by its corresponding water footprint in 1999 and 2018 to get the crop water productivity at the Cap Bon regional level over time.

4.2 Used Data

The rainfall data for the period (1999–2018) was gathered from 2 meteorological stations thus allowing for calculation of the green water consumption for different crops.

Agricultural data (crop yield and area sown) are obtained from the CRDA. Data on surface water, groundwater, and water withdrawals for irrigation were also obtained from the CRDA. Annual water diversions into different irrigated perimeters. Because these datasets were restricted to official records, they did not reflect private and uncontrolled abstractions. The resulting database was mostly fragmentary, and the gathered information was analyzed to ensure data reliability. Data on harvested tomato, citrus and wheat areas in Tunisia were also obtained from the CRDA statistical reports. Statistics on total crops production between 1999 and 2014 were obtained from the CRDA. The dataset used for implementing WF involved the Cap Bon regional scale corresponded to the management of water resources by the CRDA institutional service.

5 Results and Discussion

5.1 Water Foot Print

The blue WF has been taken as being equivalent to the proportion of the consumed irrigation water by the crops yields. The total production WF for the irrigated schemes in the region is the summation of blue and green WF of each irrigated scheme. The Fig. 3 shows the high variability of the annual blue WF among different irrigated schemes in the Cap Bon region in 2014. The blue WFs average is about 1.49 Mm^3 per year and varied from 0.06 Mm^3 to 9.62 Mm^3 per year. Differences in the estimated blue WF values among irrigated schemes reflect the different agro-climatic conditions, the crop type and the overall management practices that affect the application efficiency. For the blue WF, the irrigation efficiency should possibly be indicated. Therefore, it reveals the significant potential for improving the efficiency of irrigation water resources management. The annual blue water footprint in all the Cap Bon region and for all the irrigated crops together is fluctuating and gradually increased from 40 Mm^3 in 1999, peaked in to 63 Mm^3 in 2008 and kept relatively stable around 55 Mm^3/yr between 2008 and 2014 (Fig. 3). High amounts of WF corresponding to the occurrence of meteorological drought periods and lower amounts related to wetter years. Over the period, 1999–2008, the average of total blue WF for crop production was about 351 Mm^3/yr. Evidence from water balance analyses on farmers' fields in the hilly Kamech catchment (Cap Bon) shows that only a small fraction of rainfall (generally less than 20%) generates blue water flow (runoff), and (about 70%) is used as productive green water flow (plant evapotranspiration) supporting plant growth [4].

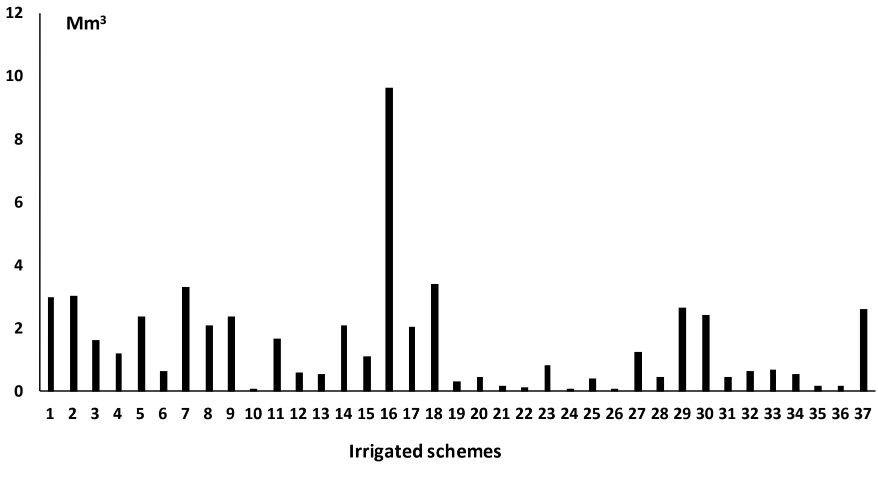

Fig. 3 Production water footprints (blue) per irrigated schemes in the Cap Bon region in Tunisia for 2014. *Source:* [28]

The annual average (between 1991 to 2014) of green WF, which corresponds to the total precipitation infiltrated in the soil for crop production, is equal to 1470 mm^3. It varies from about 730 Mm^3 in 1994 to 2400 Mm^3 in 2003. According to our estimation in rainfed Lebna catchment (210 km^2) in the central Cap bon, the average amount of green water stored in the soil between 1991 and 2014 is about 90 Mm^3. It varies from 45 Mm^3 (1994) to 150 Mm^3 (2003). Its value approximates three to five times the amount of the blue water stored at the reservoir storage capacity at its construction (30 Mm^3). It represents a renewable water resource if is managed efficiently and used by crops.

The overall temporal dynamics of the different sources of blue WF fluctuated (Fig. 4). This can be explained by the inter-annual rainfall variability and the development of irrigated citrus area that led to the WFblue increase. But as we can see, the irrigated tomato area is reduced in relation to socioeconomic reasons. We observe that the temporal dynamics of total crop production (either citrus or tomato) were similar to the dynamics of WF of irrigated agriculture in the Cap Bon region.

The yields for tomato are 41% higher in average in comparison to citrus. It is evident that wheat generally have lower yields than tomato and citrus and consequently have higher green WFs despite its lower crop water consumption per hectare.

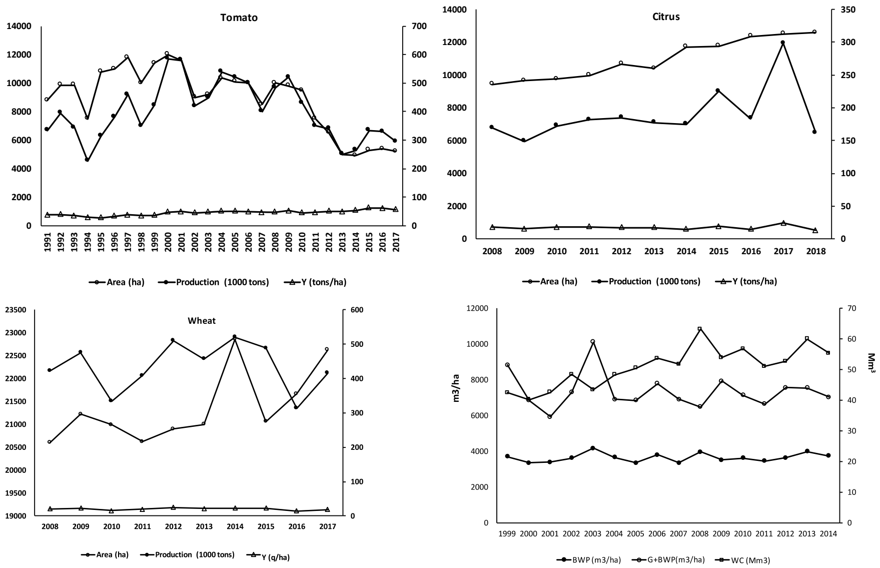

Fig. 4 Temporal dynamics of different types of water footprints (blue and green) and average annual irrigation water use per ha from 1999 to 2014 (d). Evolution of harvested areas, total annual production and yields **a** tomato, **b** citrus fruit production, and **c** wheat in the Cap Bon region in Tunisia

Table 1 WF and WP for wheat production

	2008	2009	2010	2011	2012	2013	2014	Average
WP (kg/m^3)	0.82	0.51	0.45	0.62	0.62	0.61	0.69	0.61
WF (m^3/ton)	1224.4	1964.3	2212.5	1603.7	1607,7	1634,7	1445,0	1670

Table 2 Comparison of the results of this study (Cap Bon, Tunisia) with the green WF values of some countries in the world [6]

Country	Iran	Russia	Turkey	USA	Cap Bon	Syria	Iraq	India	World	China	Egypt
WFgreen (m^3/ton)	2412	2359	2081	1879	1670	1511	1226	635	1279	820	216

5.2 Green Water Footprint of Wheat

Table 1 illustrates that wheat have a high green WF per ton of production across all years. The Table 2 shows the WF of wheat in m^3/ton for main countries producing wheat in the world. The Cap Bon WF per ton of wheat (1670 m^3/ton) obtained in this study is equal to the world average (1620 m^3/ton) [20, 22, 29]. This is in contrast with crop water use per hectare, which is the lowest for all climatic seasons. It is evident that wheat generally have lower yields than citrus and tomato, consequently have higher green WFs despite their lower crop water consumption per hectare compared to the two high consumption crops. The annual average green water productivity in the Cap Bon region for wheat crops is also fluctuating (Table 1). The average crop water productivity is about 0.61 kg/m^3 decreased from 0.82 kg/m^3 in 2008 to 0.45 kg/m^3 in 2010. Water productivity is very low in rainfed agriculture, thus providing significant opportunities for producing more crops with less water. It could be seen that productivity remains very low in spite of significant total rainfall amount during the winter season. The occurrence of drought spells and infrequent rainfall events during the post an thesis period are the most likely causal factors of low yields.

Green water, has a lower opportunity cost compared to the blue water [6–8, 29]. There are still opportunities to lower the green WF by increasing production from the rainfed, which will reduce the need for production from the irrigated water, and thus reduce blue water use.

5.3 Blue and Green Water Footprint of Tomato

Table 3 shows that tomato have the smallest WF with an average of 131.28 m^3/ton.WF values estimated in this study are significantly different from those reported by [7, 8] as global averages for WF total (214 m^3/ton), WFgreen (108 m^3/ton), WFblue (63 m^3/ton).

Table 3 WF and WP for tomato production

	2008	2009	2010	2011	2012	2013	2014	Average
WP (kg/m^3)	9.44	6.89	7.66	7.61	7.00	8.10	7.15	7.70
WF (m^3/ton)	105.9	145.1	130.4	131.4	142.7	123.6	139.8	131.28

Table 4 WF and WP for citrus production

	2008	2009	2010	2011	2012	2013	2014	Average
WP (kg/m^3)	2.76	1.83	2.34	2.53	2.18	2.26	2.05	2.28
WF (m^3/ton)	361.5	545.6	426.4	394.3	456.9	442.4	487.5	444.9

The annual average crop blue-green water productivity in all the Cap Bon region for tomato crops is also fluctuating (Table 3). The average crop water productivity decreased from 9.44 kg/m^3 in 2008 to 7.15 kg/m^3 in 2014. Comparisons across seasons revealed that in an average year, approximately 80% of crop water requirements were met through blue water and 20% via green water. On average, blue water use increased in the dry year and decreased in the wet year. This was primarily due to the difference in climatic conditions for each year.

There is a trade-off between higher crop water productivity and increasing water pollution resulting from the loss of fertilizer to the groundwater system. This trade-off needs to be considered carefully because maximizing water productivity may result in deteriorating water quality through nutrient pollution and salinization.

5.4 Blue and Green Water Footprint of Citrus

Table 4 shows that citrus mainly *Maltaise* have an average WF of 445 m^3/ton. The annual average crop blue-green water productivity in all the Cap Bon region for citrus crops is also fluctuating (Table 4). The average crop water productivity is about 2.28 kg/m^3 and decreased from 2.76 kg/m^3 in 2008 to 1.83 kg/m^3 in 2009.

5.5 Sustainability of the Water Footprint

The blue WF that specifically relates to groundwater consumption represents 62% of the total renewable groundwater resources, which means that the region is facing severe water scarcity related to the groundwater [23]. The consumptive use of groundwater exceeds the renewable groundwater available in this region.There is tremendous pressure on water resources due to the increasing demand of production of tomato and citrus with major exports. With free access to irrigation water, individual strategies varied tremendously between farmers. Drip irrigation is primarily used to achieve the highest yield; however, the water demand is not reduced. The improved technologies (powerful pumps, drip fertigation) induced a substantial increase in water productivity by optimizing the production process, conversely, it did not save irrigation water and did not decrease the water demand. Changing high water consumption cropping systems, developing efficient water-saving irrigation technology should be considered for the future agricultural management to help ensure water use sustainability and agricultural production simultaneously.

The first result of this study shows that wheat in the Cap Bon region are embedding a higher volume of green WF compared to citrus trees and tomato crops. Wheat has the largest WF per unit of weight. Policy for water governance to increase agricultural production, should be conveyed to upgrade rainfed agriculture by implementing new levers of sustainable management. Investments in rainfed agriculture have focused on remediating the negative effects of water upstream (erosion control and water conservation) to reduce the downstream impact. Field studies in Cap Bon region have shown that watersheds can have green water yields up to 3 times greater than blue water production at the reservoir downstream. Investments in crop technologies and integrated watershed management interventions could bring a shift in cropping pattern, increased yields and use more sustainable the water resouces. Crop diversification with inclusion of higher value crops such as vegetables, medicinal and aromatic plants could make the systems more sustainable and remunerative. The reduction of WF values could be achieved through irrigation management strategies that increases the water use efficiency [24]. As observed by [30] across the different climate regions of the world, large increase in crop yields is achievable for most crops through proper nutrient, water and soil management. The case study of WF of irrigated sugarcane by [25] in a rainfall scarce region of Nigeria, indicated high values of blue WF resulting from high irrigation water dependency. However, although climatic and soil factors are important in determining evapotranspiration from crop fields and yields, the green–blue WF of crops is largely determined by crop management [8, 20, 21, 23]. Generally rainfed yields depends on the additional water, but also on used crop varieties and the nutrient supply.

5.6 Spatial and Temporal Scales

The local scale is important when considering water issues. The high variability of the individual and the collective strategies of water management might explain the high variability of the WF. The evaluation of the WF considering space and time is prerequisite to distinguish levers for best water resource management.Higher spatio-temporal resolution of maps based on either local measurements or remote sensing may help to reduce the uncertainties in the assessment of WF. Specific local conditions including the daily rain pattern and partitioning between green and blue water, the cropping cycle pattern (planting and harvesting dates and thus the length of the growing period type, the rooting depth) and the local irrigation management may affect the water footprint estimates. As an example, a crop grown during wintertime can have less water consumption than when grown during spring–summer time, simply because the evaporative demand of the atmosphere is less in the winter than in the spring–summer. Similarly, the same crop grown in different locations having different evaporative demand of the atmosphere (locations more in the north or more in the south of a region), may have different water consumptions. A way to formalize this concept is through the formulation of the crop water requirement.

6 Conclusion and Perspectives

This study provided a quantitative calculation of the crop production WF over the Cap Bon region, northesstern Tunisia with semiarid climate and rainfed and irrigated farming practices. Although this study did not provide a comprehensive environmental and socio-economic assessment (considering the farming system, the growing cycle and the varieties), it did provide a useful method to facilitate an integrated water resources management. WF and WP indicators can be used in weighing up decisions and highlighting potential issues that could be investigated further so that better recommendations can be made. The available data along the last decades allowed us to assess the green and blue WF values for wheat, tomato and citrus crops. The results show that the average of total WF of crop production was about 1821 Mm^3/yr (85% green, 15% blue) over the period 1999–2008. The total WF (green + blue) of tomato and citrus crops averaged 131.28 m^3/ton, 445 m^3/ton, respectively. The green WF of wheat obtained in this study was about 1670 m^3/ton, which is equal to the calculated world average (1620 m^3/ton) by previous studies. This indicates that large opportunities for improving water footprint are found in low yielding farming systems, particularly in rainfed agriculture (water productivity is already higher in irrigated agriculture because of better yields). Also, the development of irrigated agriculture, and significant improvements in blue WF induced a large pressure on water resources. The few degrees of freedom for blue water development, calls for increased efforts to develop green water flows and upgrade rainfed agrosystems to capture the local blue water resources and increased consumption of green water before rainfall turns into blue runoff flows. One main conclusion perhaps is the need for a better assessment of green water needs for the sustainability of the agrosystems. Another relevant pending question is how to cope with the great variability of rainfed agriculture due to the normal climate variability, independently of the relevance of climate change.We acknowledge, though, that further studies may refine the quatification of WF and WP into local scale, based o applied water and on claculated crop evapotranspiration to account for the climatic variability. Also, investigating the upstream-downstream water flows of regional agricultural production is needed.

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Tunisian Marine and Terrestrial Living Environment

Producing Barbarine Lambs on Tunisian Rangelands Could be Sustainable and Provide Healthy Meat

Linda Majdoub-Mathlouthi, Hania Hamdi, and Khemais Kraiem

Abstract The objective of the paper is to present a synthesis of data concerning growth performances, carcass traits and meat fatty acid composition of lambs produced on different rangelands of the arid and semi-arid regions of Tunisia and to discuss the sustainability of this system. Based on data, lambs reared on rangeland or indoor, with concentrate supplementation have same ADG and carcass performances (P > 0.05). However, carcass produced on rangeland was less fatty, with a lower kidney, tail, subcutaneous and shoulder fats (P < 0.001). Moreover, meat lamb produced on rangeland was more dietetic because of lower intramuscular fat (P < 0.01), lower level of MUFA and a higher level of PUFA (P < 0.001). Rearing lambs on rangelands increased (P < 0.001) n-6 PUFA and n-3 PUFA, especially long n-3 PUFA. The type of rangeland has a significant effect on the n-3 PUFA, with a higher level for natural shrubs rangeland. Due to the degradation and to the low productivity of rangelands, producing lambs on rangeland could present some problem of economic viability, since the productivity is moderate. Improving rangeland quality and management could be a solution to improve the productivity. Moreover, a better valorisation of meat produced on rangeland could improve the economic viability and encourage farmers to maintain this system and to keep economic activity in poor rural areas.

Keywords Rangeland · Lamb meat · Fatty acid composition · Sustainability

1 Introduction

Traditionally, sheep production was considered as the main activity in the arid and semi-arid regions of Tunisia. It represented the principal source of income for the rural population. It was based on the valorisation of the natural rangelands and the Barbarine sheep, the autochthonous fat-tailed breed. Barbarine is well adapted to harsh conditions because of its capacity to deposit and mobilise fat reserves. In the

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last three decades, a large area of grasslands was converted to croplands for cereals, vegetable and fruit trees. Rangelands were degraded because of the animal high pressure exerted. The contribution of rangelands to livestock feed decreased progressively. In North Africa, it contributed by less than 20% of livestock requirements [1].

In Tunisia, rangelands contributed by 65% in the sixties. In the last decade, contribution regressed to 10–25% [2]. Therefore, farmers use more and more the intensive and semi-intensive system for growing and fattening lambs [3]. Feeding is based on oat hay and concentrate which are expensive. Oat hay price is very fluctuant and depends on rainfall. The concentrate components (maize, soybean, barley, …) are mainly imported and with ever-increasing prices. To reduce the cost of concentrate, many farmers used barley seed and/or bran. So, the supply of protein could be limited.

On the other hand, it is well established around the world, that meat lamb produced in extensive systems, on pasture and rangeland is characterised by a typical sensorial quality and a higher dietetic quality. The fatty acid composition is characterised by a higher level of n-3 PUFA and especially longs n-3 PUFA, that are recognized to have a beneficial effect on human health. An increase of long n-3 PUFA intake is recommended, to reduce the risk of cardiovascular diseases, some cancers and obesity [4]. Also, Meat lipids produced on pasture, and despite the higher PUFA content, are more stable to oxidation, during storage because of a higher supply of antioxidants (Vitamine E, polyphenols.). The effect of pasture or rangeland on fatty acid composition and lipid oxidation depended on the floristic composition. Therefore, meat lamb produced in rangeland can be classified among traditional products that can have a quality certificate. Delivering a quality sign for Barbarine lamb fattened on rangeland could promote this production system and motivate farmers to maintain it. In this paper, in the first part, we present a multifactorial analysis of experimental data and a synthesis concerning growth performances, carcass traits and meat fatty acid composition of lambs produced on different rangelands of the arid and semi-arid regions of Tunisia. In a second part, we present some reflexions concerning the sustainability of this system.

2 Lamb Production on Tunisian Arid Rangeland: A Synthesis of Trials Data

2.1 Data Description and Statistical Analysis

Data concerned 87 male Barbarine post weaning lambs. These animals were used in four experimental trials comparing carcass traits and meat fatty acid composition between lambs reared on rangeland from the arid and the semi-arid region of Tunisia and lambs reared indoor with oat hay. For the two feeding systems, lambs were supplemented with concentrate (100 à 500 g/d), in order to maintain the same ADG between the groups of each trial. The rangelands belong to three sites of the Tunisian

Table 1 Sites characteristics and floristic composition of rangelands

	Sidi Bouzid				Zaghouan Saouef (OEP)	
	Sidi Bouzid Est (Touila)		Menzel Bouzaine (El Ettizez)			
Region	Lower semi-arid		Arid		Upper semi-arid	
Pluviometry (mm)	200–350		100–200		350–600	
Type of rangeland	Shrubs pasture		Herbaceous pasture		Herbaceous + shrubs pasture	
Floristic composition (%)	*Peganum harmala*	13.0	*Cynodondactylon*	62.3	Medicago Arborea	88.7
	Lygeumspartum *Salsolatetrandra* *Stipagrostispungens*	13.1 11.2 11.1	*Sisymbriumirio*	20.7	Calicotomevillosa	4.8
	Atracylisserratiloides	7.3	*Anagallis arvensis*	4.9	Atriplexhalimus	2.0
	Suaedamollis	4.5	*Medicago ciliaris*	3.3	Acacia Cyanophylla	2.0
	Lymoniastrumguyonianum	4.4	*Convalvulusarvensis*	2.0	**Herbaceous species**	
	Rhanteriumsuaveolens	6.0	*Chenopodium murale*	1.5	Stipaparviflora	48.4
	Artemisia compestris	3.2	*Launeaenudicaulis*	1.4	Cynodondactylon	24.05
	Artemisia herba-alba *Echiochilonfruticosum*	5.6 6.2	Others	3.9	Plantago albicans	5.0
					Asteriscusmaritimus	3.4
					Atractyliscancellata	2.92

SW: slaughter weight, CC: cold carcass weight, HPC: high priced carcass weight, MC: meat carcass weight, SM: shoulder muscle weight, SF: shoulder fat weight, TF: tail fat weight, KF: kidney fat weight, SFT: subcutaneous fat thickness, CL: carcass length, LL: leg length, LC: leg circumference, RC: rump circumference, CD: chest depth arid and semi-arid region (Sidi Bouzid Est; Menzel Bouzaine; Saouef, Zaghouan). The three sites were characterised by different edaphic and climatic conditions.Three types of pasture were used: Natural shrubs pasture (SP), Herbaceous pasture (HP) and fodder Shrubs and herbaceous pasture (SHP). Floristic composition of rangelands was different between trials (Table 1). Lambs fattening period vary between 60 and 240 days depending on trials and feeding system. Body weight was recorded every 21 days in order to estimate average daily gain (ADG). All lambs were slaughtered at the same conditions, in the same slaughter house, according to the Muslim rite after a fasting period of 12 to 16 h with free access to water. Offals were removed, the carcass was chilled for 24 h at 4 °C, then cut into seven cuts and deboned as described in [3]. High priced cuts (leg, shoulder and loin) as well as carcass meat were weighed. The shoulder was dissected into bone, muscle and fat. Carcass fatness was estimated by the kidney and tail fats weight and the subcutaneous fat thickness. Rump circumference, chest depth, leg length, leg circumference and internal carcass length were measured to appreciate carcass conformation according to [3]. Muscle samples of Longissimus lumborum was ground and used for the analysis of intramuscular fat using the method of [5]and fatty acid composition by gas chromatography-flame ionisation.

Data concerning animal performances ($n = 2$), carcass traits ($n = 13$)and meat fatty acid composition ($n = 11$) were treated using the principal component analysis (PCA) of STATISTICA (version 5.5, StatSoft, Tulsa, OK, USA). Four PCA were realised. Two PCA were used for variables concerning animal performances and carcass traits to represent the effects of rangeland access and the rangeland type. Two other PCA were realised for variables concerning fatty acid composition. Only the variability explained by the axes of the PCA with eigenvalues > 1.0 was taken into account.

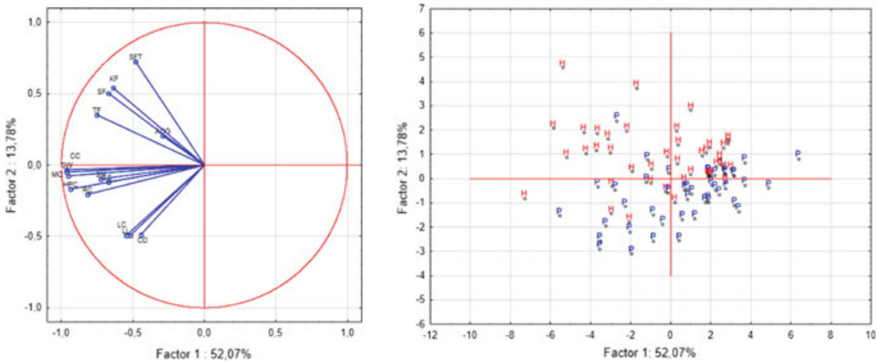
A one-way ANOVA was then used to study the effect of feeding system (Hay vs Rangeland) and the effect of rangeland type. The standard error of the mean (SEM) was used as the error term. Ls means were compared using the Duncan test and results were considered significant when $P < 0.05$.

2.2 Results

2.2.1 Growth Performances and Carcass Traits

Effect of the Rangeland Access

About seventy-three percent (73.12%) of the variability of growth performances and carcass traits was explained by three axes having an eigenvalue > 1.0. The first axe explained 52.07% of the variability (Fig. 1a) and was supported by slaughter weight (SW), cold carcass weight (CC), high priced cuts weight (HPC), Meat carcass weight (MC), shoulder muscle weight (SM), shoulder fat weight (SF), tail fat weight (TF) and rump circumference (RC). All these variables were highly correlated to SW. The second axe explained 13.76% of the variability and was represented by subcutaneous



a. projection of variables **b. projection of cases**

Fig. 1 Effect of pasture access on growth performances and carcass traits of Barbarine lambs

fat thickness (SFT), perirenal fat (PF) and SF. All fatness variables were correlated. The third axe explained 7.28% of the variability and was represented by ADG.

Cases projection on the first and second axes, indicated discrimination between lambs reared indoors and lambs reared on rangeland (Fig. 1b). SW, ADG, CC, CY, HPC, MC, SM, RC were not different ($P > 0.05$) between pasture group and indoor group (Table2). However, SFT, TF, SF and KF were respectively higher ($P < 0.001$) by 114.36%, 58.11%, 45,46% and 45.29% for the indoor group (Table 2).

In conclusion, lambs reared on pasture were less fatty than those reared indoor, despite the same slaughter weight, the same fattening period and the same ADG.

Effect of the Rangeland Type

The three axes with an eigenvalue > 1 explained 75.39%. The first axe explained 54.19% of the variability and was supported by SW, CC, HPC, MC, SM, SF, TF, RC and carcass length (CL). The second axe explained 13.22% of the variability and was represented by SFT and KF. The third axe explained 8.8% of the variability and was represented by ADG (Fig. 2a). Projection of cases on the (1×2) plane did not indicate a net distinction between the two groups (SHP and HSHP). The HP group was separated. Data concerning the three groups was presented in Table 3. ADG was not different ($P > 0.05$) between groups. Whereas, SW tended to be lower ($P = 0.06$) for HSHP. Therefore, CC, HPC, MC and SM were lower ($P < 0.05$) for HSHP. KF and TF were also lower ($P < 0.01$) for HSPH. Differences noted for HSHP were probably associated with differences in SW and CC.

Table 2 Effect of pasture access on growth performances and carcass traits of Barbarine lambs

	Pasture + concentrate N = 44	Hay + concentrate N = 43	SEM	P-values
Fattening period (d)	127.00	125.00	52.00	
SW (kg)	33.66	35.58	0.55	0.08
ADG (g/d)	87.72	94.72	3.27	0.29
CC (kg)	15.10	16.09	0.30	0.10
CDP (%)	45.05	45.00	0.30	0.94
HPC(g)	4175.78	4258.65	70.04	0.58
MC (g)	5372.76	5698.79	123.00	0.18
SM (g)	838.27	797.94	14.28	0.18
Carcass fatness				
SF (g)	148.77	216.55	7.64	0.001
TF (g)	928.75	1468.50	58.78	0.001
KF(g)	81.08	117.80	5.30	0.001
SFT (cm)	1.81	3.88	0.21	0.001
Carcass conformation (cm)				
CL	60.93	59.65	0.48	0.19
LL	39.41	38.18	0.23	0.01
LC	36.78	36.86	0.34	0.91
RC	57.67	59.22	0.44	0.07
CD	27.24	26.89	0.17	0.31

SW: slaughter weight, CC: cold carcass weight, HPC: high priced carcass weight, MC: meat carcass weight, SM: shoulder muscle weight, SF: shoulder fat weight, TF: tail fat weight, KF: kidney fat weight, SFT: subcutaneous fat thickness, CL: carcass length, LL: leg length, LC: leg circumference, RC: rump circumference, CD: chest depth

2.2.2 Meat Nutritional Quality

Effect of the Rangeland Access

Three axes explained 69.31% of the data variability. The first axe explained 48.62% of variability and was represented by C18:1n-9, C18:2n-6, C18:3n-3, C40:4n-6, C20:5n-3 and C22:5n-3. The second one explained 13.53% and was represented by C18:0 and the third axe explained11.33% and was represented by CLA (Fig. 3a). Projection of cases on the first and second axes indicated that meat fatty acid composition was separated between lambs reared indoor and lambs reared on rangeland (Fig. 3b). Cases for indoor lambs were regrouped, whereas those of rangeland group were scattered. Some cases concerning rangeland lambs were mixed with the indoor group.

Variance analysis results are represented in Table 4. Intramuscular fat was higher for indoor lambs (2.83 vs 2.31%, $P < 0.01$). C16 and C18:1n-9 levels were also higher for indoor lambs ($P < 0.05$; $P < 0.001$). Whereas, C18:2n-6; C18:3n-3; C20: 4n-6; C20: 5n-3 and C22: 5n-3 percentages were higher for rangeland lambs ($P < 0.01$). No difference was noted for C18:0 and CLA.

As a result, the total saturated fatty acid proportion (SFA) and unsaturated fatty acid were not modified ($P > 0{,}05$) by feeding system. Monounsaturated fatty acid (MUFA) proportion was lower ($P < 0{,}001$) by 3.72% and polyunsaturated fatty acid proportion was higher ($P < 0.001$) by 3.85% for rangeland lambs. Feeding lambs on

Table 3 Effect of pasture type on growth performances and carcass traits of Barbarine lambs

	SHP N = 20	HP N = 12	HSPH N = 12	SEM	P-values
Fattening period(d)	164	103	88	7.19	
SW (kg)	34.07	35.45	31.17	0.69	0.06
ADG (g/d)	83.42	88.40	94.59	31.87	0.63
CC (kg)	15.39[a]	16.52[a]	13.18[b]	0.40	0.01
CY (%)	44.16[b]	44.97[ab]	46.53[a]	0.36	0.02
HPC (g)	4230.23[a]	4516.96[a]	3739.32[b]	99.55	0.01
MC (g)	5572.98[a]	6050.83[a]	4344.32[b]	175.79	0.001
SM (g)	827.08[a]	927.80[a]	768.32[b]	22.29	0.02
Carcass fatness					
SF (g)	149.00	151.66	145.49	7.53	0.95
TF (g)	955.72[a]	1130.87[a]	679.44[b]	58.00	0.01
KF (g)	71.12[b]	109.75[a]	69.85[b]	5.69	0.01
SFT (cm)	1.70	2.08	1.74	0.14	0.50
Carcass conformation (cm)					
CL	61.00[ab]	63.17[a]	58.58[b]	0.58	0.01
LL	39.76	39.58	38.67	0.28	0.26
LC	38.36[a]	34.79[b]	36.00[ab]	0.54	0.02
RC	59.40[a]	55.71[b]	56.58[ab]	0.63	0.02
CD	27.52	26.54	27.46	0.23	0.20

SW: slaughter weight, CC: cold carcass weight, HPC: high priced carcass weight, MC: meat carcass weight, SM: shoulder muscle weight, SF: shoulder fat weight, TF: tail fat weight, KF: kidney fat weight, SFT: subcutaneous fat thickness, CL: carcass length, LL: leg length, LC: leg circumference, RC: rump circumference, CD: chest depth

pasture increased (P < 0.001) total n-3 PUFA and n-6 PUFA percentages by 1.05% and 2.59%, respectively. The n-6 PUFA/n-3 PUFA and PUFA/SFA ratios were also higher (P < 0.001) for pasture group.

Effect of the Rangeland Type

Three axes explained 49.84%, 14.27% and 10.76% of the data variability, respectively (Fig. 4a). Projection of cases (Fig. 4b) on the factor plane (1 × 2) indicated that the HP group was different from the two other groups (SHP and HSHP). Fatty acid composition for the three groups was summarized in Table5. Intramuscular fat was not different (P > 0.05) between the three pasture types. The SFA was lower (P < 0.01) for the HP group. The C16:0 was not modified by the floristic composition whereas C18:0 acid was lower (P < 0.001) for the HP group.The MUFA proportion was higher (P < 0.001) for the HP group.The principal MUFA (C18:1n-9) was higher (P < 0.01) for the HP group, whereas there was no difference between SHP et HSHP. For the PUFA, pasture type altered particularly n-3 PUFA proportion (P < 0.01), whereas n-6 PUFA proportion was not modified. As a result, total PUFA proportion was not different between the three groups.

For the n-3 PUFA, C18: 3n-3 proportion was higher (P < 0.001) for SHP group (1.48% vs 0.95% and 0.77% for HSHP and HP groups, respectively). The C 20:3n-3 and the C22:3n-3 proportions were also higher (P < 0.05) for SHP group. However, for the n-6 PUFA, C18:2n-6, CLA and C20:4n-6 were not modified (P > 0.05) by

Table 4 Effect of rangeland access on the principal fatty acid (% of total fatty acids) in longissimus lumborum muscle in Barbarine lambs

	Pasture + concentrate N = 44	Hay + concentrate N = 43	SEM	P-values
Fat (%)	2.31	2.83	0.09	0.01
C16:0	20.71	21.85	0.23	0.05
C18:0	20.47	20.50	0.28	0.96
C18:1n-9	34.23	38.04	0.44	0.001
C18:2n-6	7.66	6.01	0.21	0.001
c9, t11C18:2	0.42	0.41	0.01	0.56
C18:3n-3	1.14	0.63	0.05	0.001
C20:4n-6	2.17	1.46	0.10	0.01
C20:5n-3	0.30	0.11	0.02	0.001
C22:5n-3	0.52	0.28	0.03	0.001
C22:6n-3	0.16	0.04	0.01	0.001
SFA	46.16	46.80	0.39	0.41
MUFA	36.35	40.07	0.45	0.001
PUFA	13.71	9.86	0.41	0.001
n-6 PUFA	10.78	8.19	0.33	0.001
n-3 PUFA	2.11	1.06	0.10	0.001
PUFA/SFA	0.30	0.21	0.01	0.001
n-6 PUFA/n-3 PUFA	6.05	8.59	0.34	0.001

SFA: saturated fatty acid, MUFA: monounsaturated fatty acid, PUFA:polyunsaturated fatty acid

the rangeland type.PUFA/SFA and n-3PUFA/n-6 PUFA ratios were not modified by the type of pasture.

2.3 Discussions

2.3.1 Growth Performances and Carcass Traits

In the different trials, ADG of lambs reared on rangelands of the arid and semi-arid regions and supplemented with 100 to 400 g/d of concentrate averaged 87.7 g/d and was not different from that of lambs reared indoor and received a moderate supply of concentrate (300–500 g/d). The floristic composition of the three rangelands used in this synthesis indicated the dominance of species resistant to drought and hard conditions such as *Cynodon dactylon* and *Sisymbriumirio* for herbaceous species and *Salsola tetrandra* and *Lygeum spartum* for natural shrubs. The pastoral value for the herbaceous strate for two rangelands of them [6, 7] was average, because of the low contribution of legumes family. The ADG obtained in the different trials was moderate compared to that (150 and 200 g/d) obtained for Barbarine lambs reared in more favourite conditions. [8] reported a higher ADG for Barbarine lambs reared on the natural or cultivated pasture of the north region of Tunisia. Depending on biomass and nutrient availability, ADG of lambs reared on pasture could be similar

Table 5 Effect of pasture type on the principal fatty acid (% of total fatty acids) in longissimus lumborum muscle in Barbarine lambs

	SHP N = 20	HP N = 12	HSPH N = 12	SEM	P-values
Fat	2.27	2.58	2.09	0.10	0.18
C16:0	20.17	21.62	20.70	0.30	0.13
C18:0	21.50[a]	17.04[b]	22.30[a]	0.48	0.001
C18:1n-9	33.40[a]	37.36[b]	32.50[a]	0.57	0.01
C18:2n-6	7.9	7.04	7.90	0.32	0.49
c9, t11C18:2	0.43	0.35	0.48	0.02	0.06
C18:3n-3	1.48[a]	0.77[b]	0.95[b]	0.09	0.001
C20:4n-6	1.09	1.26	0.72	0.16	0.08
C20:5n-3	0.38[a]	0.17[b]	0.29[ab]	0.03	0.02
C22:5n-3	0.66[a]	0.37[b]	0.42[ab]	0.05	0.02
C22:6n-3	0.13[b]	0.26[a]	0.08[b]	0.02	0.05
SFA	46.35[a]	43.49[b]	48.52[a]	0.59	0.01
MUFA	35.34[b]	40.01[a]	34.38[ab]	0.59	0.001
PUFA	14.81	12.52	13.06	0.62	0.26
n-6 PUFA	11.45	10.09	10.36	0.50	0.47
n-3 PUFA	2.65[a]	1.56b	1.75[b]	0.16	0.01
PUFA/SFA	0.32	0.30	0.27	0.02	0.44
n-6 PUFA/n-3 PUFA	5.69	6.62	6.09	0.38	0.61

SFA: saturated fatty acid, MUFA: monounsaturated fatty acid, PUFA: polyunsaturated fatty acid

or higher than that of lambs reared indoor. In some studies, the pasture type or the floristic composition of the pasture could influence the ADG. Lambs reared on mixed pasture had higher ADG than those reared on ray-grass dominant pasture [9]. Moreover, lambs raised on legume pasture had higher growth performances than those fed grass [10]. The difference is probably due to the supply of energy and protein. Increasing concentrate supply could also increase ADG [3, 11]and slaughter weight, but it can deteriorate the carcass fatness.

It is also interesting to note, that grazing lambs had similar carcass weight, carcass yield and meat carcass weight than indoor lambs. They also have the same conformation. These criteria are very important to producers and butchers.

In this review, despite the same slaughter weight and ADG, carcass produced on rangeland and concentrate was less fatty, with a lower kidney, tail, subcutaneous and shoulder fat than that produced indoor with hay and concentrate. In several studies, carcass fatness difference was attributed to higher ADG or a higher SW observed for the indoor lambs [12–14]. For this synthesis, higher energy requirements for physical activity when grazing could explain the lower carcass fat, as also mentioned by [15]. [16] reported that lambs reared on pasture have a different feeding behaviour and have more physical activity, and these activities increased the first mobilisation of lipid reserve than that of energy reserve in muscle, which explain the lower fatness for rangeland lambs. It could also be associated with the capacity of the rustic breed, adapted to harsh conditions, to mobilise lipid reserve to have energy for survival when feed energy supply is limited.

The rangeland type affected carcass traits. The difference seems to be mainly due to differences in slaughter weight. Effects of rangeland or pasture type on carcass traits were controversial and could be explained by differences in the nutritive quality of pastoral plants, physical activity, and slaughter weight [16].

2.3.2 Meat Nutritional Quality

Intramuscular fat has an important effect on juiciness, tenderness and flavour of meat [17]. Australian consumers consider that lamb meat is acceptable, when intramuscular fat content is between 3 and 7.3%. Palatability was improved when increasing intramuscular fat level. In Tunisia also, consumers traditionally preferred meat with a high level of intramuscular fat. In the last decades, consumers become more aware of healthy food and looked for lean meat. Young people preferred lamb meat with less pronounced flavour. Producing lamb meat on rangeland with a moderate concentrate supplementation can meet the current consumer demand. Lambs produced on rangeland had lower intramuscular fat content (2.3 $\pm$ 0.66%) than those fed indoor with hay and concentrate (2.8 $\pm$ 0.91%), which was coherent with results concerning kidney, subcutaneous and intermuscular fats. In a metanalysis study, [18] reported that grazing lambs tended to have lower intramuscular fat content, but there were controversies between studies. They explained this heterogeneity by the presence or not of supplementation to concentrate. [15] reported a higher fat level for indoor lambs, whereas [19] reported similar intramuscular fat content for Barbarine lambs reared on pasture or indoor with an adlibitum supply of concentrate. However, in the last study, lambs were slaughtered at 26 kg and the intramuscular fat was not well developed, since intramuscular fat increased later in the life of animals.

Fatty acid composition in lamb meat is not recommended for human health because of the high supply of SFA and MUFA and the low supply of PUFA. It is characterised by a low PUFA/SFA ratio (0.15, [20]) compared to the recommended value for human health (0.4). The C16:0 acid, which is considered as the principal hypercholesterolemic acid was abundant in lamb meat and it is responsible for increasing cardiovascular disease risks [4]). PUFA are considered important for human health, mainly n-3 PUFA and CLA. Long n-3 PUFA (C20:5n-3, C22:5n-3 and C22: 6n-3) are considered as essential nutrients for human growth. They contribute to the development of the infant brain and liver and prevention of certain diseases, cardiovascular disease risks and cancer [4].

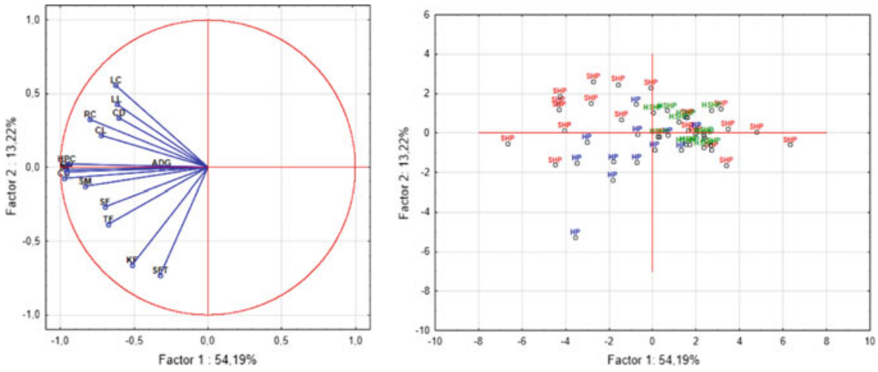
In ruminant feeding, two main strategies were used to increase the supply of n-3 PUFA level in meat, access to pasture or rangeland and use of n-3 PUFA dietary sources, such as linseed [21]. [18] and [16] reported in their reviews that access to pasture improved the supply of n-3 PUFA in lamb meat.[18] indicated an average improve 2.10%, but the improvement was variable between papers. [18] reported that proportion on n-3 PUFA for lambs reared on pasture is variable and is between 0.9 and 6.4%. This variability is associated with the nature of pasture and of supplementation. Legumes species contains a higher level of n-3PUFA than grass species. The presence of secondary compounds (condensed tanins, saponin..) in plants could reduce the ruminal biohydrogenation [22] and allowed the higher supply of PUFA to muscle. [23] reported that condensed tannin in legumes reduced rumen biohydrogenation by inhibiting the responsible microorganisms. Access to Tunisian dry rangeland had the same effect as reported for pasture. N-3 PUFA was of 2.11% and was higher by 1.05% than the indoor group. Depending on the rangeland type, the n-3 PUFA averaged between 1.56 and 2.65%. The highest percentage was observed for lamb meat produced on rangeland dominated by natural shrubs. These plants are adapted to harsh conditions and are probably rich in secondary compounds that protect PUFA against biohydrogenation. In the Tunisian north-west conditions, [24] also reported a difference in n-3 PUFA level between pasture types from different sites. Despite an increase in the percentage of EPA + DHA with rangeland access, this percentage was still lower than the value of 23 mg/100 g of meat) taken as a limit to consider lamb meat as a source of long-chain n-3 PUFA [25]. These authors reported that when lambs were reared on only green pasture until slaughter, the EPA + DHA were higher than 30 mg/100 g muscle. Whereas, if lambs were grazing lower quality pasture and/or were supplemented with concentrate, the level of EPA + DHA would be lower.

N-6 PUFA level also increased for lambs reared on rangeland, without any difference between rangeland types.This was associatedwith the increase of C18:2n-6. In their meta-analysis, Popova et al. (2015) found a decrease of n-6 PUFA level, with pasture system. As a result, access to rangeland increase PUFA/SFA ratio and decrease n-6/n-3 ratio. For grazing lambs, PUFA/SFA ratio averaged 0.3, it was higher than the ratio of 0.15 reported by [20] and got close to the ratio of 0.4 recommended for human health. The n-6/n-3 ratio averaged 6.02 and was close to the recommended value (6) given by [26].

It is also noted that lipids of lamb meat produced on rangeland of the region of Saouef, was more stable to oxidation during conservation [27]. This stability was explained by a higher supply of Vitamine E. [28] also reported that grass and green forages are rich in compounds that have antioxidant activity and protect lipids from oxidation.

3 Sustainability of Lamb Production on Rangeland

Producing lambs on rangeland present the advantage to have a dietetic, and probably safety meat, because of the little use of fertilisers, pesticides, herbicides, antibiotics, hormones genetically modified organisms [29]. The little use of chemical compounds also has a positive effect on the environment. However, in the actual conditions and due to the degradation and to the low productivity of rangelands, this production system could present some problem of economic viability, since the productivity is moderate. Improving rangeland quality and management could be a solution to improve the productivity. Moreover, a better valorisation of meat produced on rangeland could improve the economic viability and encourage farmers, and particularly the youths to maintain this system and to keep economic activity in poor rural areas.

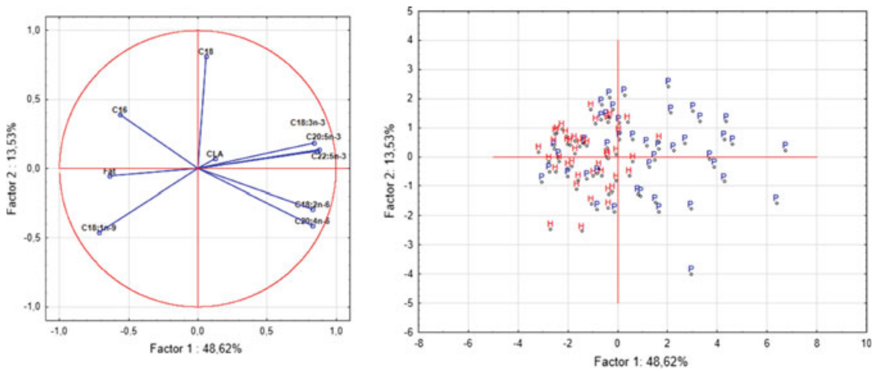


a. projection of variables **b. projection of cases**

Fig. 2 Effect of pasture type on growth performances and carcass traits of Barbarine lambs

3.1 Improvement of the Rangeland Quality

In the semi-arid region of Tunisia, Barbarine is the autochthonous breed, it is adapted to harsh conditions, valorise power nutritive quality feed and can deposit and mobilise body reserves easily. Production of lambs on rangeland is a tradition and meat is well appreciated by consumers. This product is characterized by suitable and healthy fatty acid composition. This composition depends on the rangeland floristic composition, the pasture duration and the level of concentrate supplementation. To keep this nutritional quality, lambs must be fattened and finished on rangeland. Concentrate supply should be moderate and do not exceed 400 g/d. Unfortunately, rangelands are more and more degraded, because of the animal high pressure. In the dry conditions, they are characterised by the dominance of low and medium species palatability. Their pastoral value is moderate. Overgrazing changed rangeland biodiversity from the dominance of palatable plant species to less-desirable plants [30]. Temperature increase and rainfall decrease limit pasture growth in summer and reduce rangeland yield [31]. In NorthAfrica, over the last three decades, permanent grassland areas have reduced by 5% [32]. Climate change may affect the nutritive value of consumable biomass by increasing lignification and synthesis of secondary metabolites [31]. It became thus difficult to maintain regular food supply from natural rangeland. Different strategies were tested and used to improve the quality of natural rangelands of the semi-arid region of Tunisia. The use of fodder shrubs was one of the principal strategies to improve the availability of food resources on rangeland. These shrubs are adapted to harsh conditions and could produce for a longer period than natural herbaceous plants. The shrubs could have modest digestibility, but they provide edible green foliage during summer -automn, a season with a high feed deficit and when the herbaceous pasture is senescent [33]. Some shrubs are rich in protein (10–20% DM basis) such as *Medicago Arborea* or *Atriplex Nummularia.*



a. projection of variables **b. projection of cases**

Fig. 3 Effect of pasture access on meat fatty acid composition of Barbarine lambs

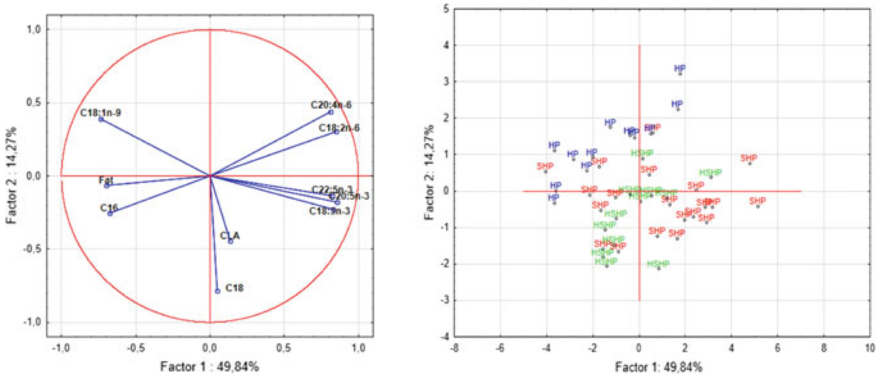
Other shrubs have a moderate protein content (13–15%), such as *Acacia Cyanophylla. Opuntia spp* represented the last group and had a low protein content (3–6%).

These shrubs have a variable level of secondary compounds (tanins, saponine), that could have an anti-nutritional effect. This negative effect is associated with the level, the origin and the physiological stage of the animal. In some conditions, condensed tanins could reduce ruminal protein degradation and fatty acid biohydrogenation which improve animal performance and meat fatty acid composition. Some secondary compounds are also recognized as having anthelmintic properties and could also decrease methane emissions. [27] reported acceptable performances and healthy fatty acid composition for lambs reared on natural rangeland improved by *Medicago Arborea.*

Mixing shrubs was reported by [31] as a possible technique to maximise the valorisation of shrubs, to balance nutrients supply and to reduce the negative effects of secondary compounds and high salinity. A combination between *Atriplex Nummularia* and *Opuntia spp* was proposed by [34]. In Tunisia, from 1990 to 2016, 142,000 ha of rangeland have been improved by *Opuntia spp.* After plantation, the feed biomass increases from 0.2 to 0.5 to 6 to 12 tons of dry matter per ha [2]. Use of fodder shrubs could also be a way to provide shade and shelter for animals, to preserve soil from degradation, to improve the organic layer, the soil fertility and to sequester carbon [33].

In the agro-pastoral system, rangeland could be improved by herbaceous, annual or perirenal plants. These plants must be resistant to drought and climate change.

An application of a pastoral rest period to the rangeland could improve the floristic composition and the biomass. [35] reported recoveries of *Artemisia herba-alba* and *Stipa tenacissima* in the highland steppe of eastern Morocco. Moreover, [36] indicated that protection of rangeland improves the species richness and the diversity. The effect of protection also depends on the rainfall and the soil type. In the arid condition of the south of Tunisia, [37] also reported that the practice of the rest technique preserve already existing species and allows the relocation of some species



a. projection of variables **b. projection of cases**

Fig. 4 Effect of pasture type on meat fatty acid composition of Barbarine lambs

with high pastoral value. However, two years of protection in Syrian semi-arid rangeland exposed to higher pression of grazing increased the herbaceous biomass and the floristic diversity, but not necessary species with high pastoral value [30].

3.2 *Valorisation of Lamb Meat Produced on Rangeland*

In order to motivate farmers to keep the agro-pastoral system in the arid and semi-arid regions, lamb meat produced in this system must be better valued, since it has high dietetic properties. The implementation of a specification that allows the lamb to have a sign of quality could be a strategy. Some consumers are more and more interested by animal products having a high nutritional and sensorial quality and they are ready to pay the difference in price without any objection, since they are sure of the authenticity of the product. The establishment of an authentication and traceability system is necessary to develop a sign of quality. Some markers have been proposed to discriminate between meats produced in different contexts and according to different food systems. [38] proposed the analysis of carotenoid, phenolic or volatiles compounds and fatty acids. Also, [24] reported that it is possible to differentiate the geographical origin of lambs using stable isotope ratios. Visible reflectance spectroscopy could have a high potential to distinguish between lambs produced on pasture and those produced indoor [39]. Although, the inclusion of chemical analysis (fatty acids, carotenoid..) could improve the discrimination (Figs. 2, 3 and 4).

4 Conclusion and Recommendations

Meat produced on rangeland has many dietetic and sensorial properties and could have a quality sign that would promote this product and keep this production system. However, considerable efforts are needed to improve the quality of rangelands and ensure their sustainability. Rangelands in Tunisia are in the majority communal and their management seemed to be very difficult. The state and the associations will be solicited to ensure a better management of these rangelands. The establishment of a GIS system for monitoring the location of grasslands, their evolution, their biomass could help organizations and local authorities to ensure a better management of rangelands. Moreover, and to boost the economic activity in the rural regions, animals produced on rangelands should be slaughtered, meat must be packaged and processed in the production zone.

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Freshwater Fish Farming and Fishery Management in Tunisian Reservoirs: Limitations and Opportunities

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Abstract With the aim of determining and evaluating the condition of freshwater fisheries in Tunisia, 14 surveys were undertaken in the most important reservoirs of the country. Specimen were collected between May 2013 and May 2016. The sampling areas are Bakbeka, Bir Mcherga, Bouheurtma, Bezirekh, Ghezela, Kasseb, Laabid, Lahjar, Mellegue, Mlaabi, Sidi Barrak, Sidi Saad, Sidi Salem, Seliana and they vary in depth and surface areas. For fish sampling in lakes, we used multi-mesh gill nets made for the purpose. We applied standard fishing methods to investigate biomass, species composition, size distribution and abundance. Eight species were caught in the prospected reservoirs: *Liza ramada*, *Mugil cephalus*, *Luciobarbus callensis*, *Sander lucioperca*, *Rutilus rutilus, Cyprinus carpio, Scardinius erythrophthalmus* and *Pseudophoxinus callensis*.

Fish abundance varied significantly according to depth strata and sampling sites. The findings showed that fishes were abundant in the upper water layers and fish biomass distribution was governed by the depth of water from the reservoir to the tributary. The most important Yields (CPUE) by weight and by number were obtained in Lahjar Reservoir (28.75 kg/1000 m^2 of nets and 446.43 fish/1000 m^2 of nets) while Mlaabi turned out to be the poorest reservoir in Tunisia. The CPUE in this dam does not exceed 0.67 kg/1000 m^2 of nets and 6.25 fish/1000 m^2 of nets. We identify a poor diversity associated with an alarming decline in stocks of autochthonous freshwater fishes in Tunisian reservoirs. The study of the functional organization of fishery groups did not show any improvement. On the contrary, 78% of the total captured

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fishes belong to a group of cyprinids against only 6% of the predators which indicates that most Tunisian reservoirs are suffering from environmental/anthropogenic stressors. However, the presence of detritus feeders (Mugilidae species) is seen as a good indicator for the environmental quality of the ecosystem.

The Shannon index (H′) and evenness (J′) classify the 14 Tunisian reservoirs among the worst sites with their bad ecological status (H′ < 1.5) inducing the presence of imbalanced structure where the community of the freshwater fisheries was dominated by a small number of species (generally one species of cyprinids). Species size distribution differed significantly from one reservoir to another and it exceeded the length at first maturity in the majority of reservoirs prospected. Composition of species was bigger and their abundance was more important in Sidi Barrak, Sidi Salem, Seliana, Sidi Saâd reservoirs than in Kasseb, Bekbeka, Ghezala, Laabid, Mlaabi and Bouheurtma.

Most of the reservoirs especially: Kasseb, Bekbeka, Ghezala, Laabid, Mlaabi and Bouheurtma need improvement action plans to enhance fish productivity and population status, such as increasing control over types of fishing gears used and the introduction of brood stock and fry fish.

Keywords Fish assemblage · Multi-mesh gill nets · Fishery management · Fish metrics · Tunisian reservoirs

1 Introduction

Pisciculture in Freshwater bodies is relatively new in Tunisia, as it dates back only to the sixties. This activity has witnessed an important growth in the nineties after the Tuniso-German cooperation project, the Deutsche Gesellschaft für Technische Zusammenarbeit, was undertaken [1]. In Tunisia, pisciculture practiced in freshwater bodies started with an experiment of stocking reservoirs with Mullet. For the first time (in 1964), 100,000 fries of *Mugil cephalus* were collected and stocked in Mellegue Reservoir. The exploitation of several freshwater reservoirs by the National Office of Fisheries took place between the years 1979 and 1988. After the introduction of Mullet fry in reservoirs, production reached around 20.3 T including Barbel (54%), Mullets (44%), and other fishes (0.5%) [1]. Since 1987, the General Secretariat of Fisheries has been delivering fishing licenses to professional fishermen in order to improve fisheries exploitation in the reservoirs. However, the total production of fish remains very low with the exception of Mullets in Bir Mcherga which increased [2].

For several decades, many solutions have been suggested in order to develop freshwater fisheries, including extensive freshwater fish farming [3–7]. However, no rational exploitation of freshwater fisheries has been conducted before the implementation of the Tuniso-German project. Additionally, the experimental freshwater fish farming failed to produce a commercial product before 1990 [8].

The majority of Tunisian reservoirs are found in the north of the country [9] and they are classified into three categories: large reservoirs, small reservoirs or landscape lakes and farm ponds (Fig. 1). Tunisian dams are varied due to the different watersheds alimenting reservoirs and to the fluctuation of the physicochemical parameters of the water [10]. Additionally, Tunisian reservoirs are considered as a macrocosm whose fish balance can be disturbed by anthropogenic activities, such as fishing or introduction of new species [11].

Freshwater fish fauna in the north of Africa, especially in Tunisian reservoirs, have a limited number of species [1, 12–15] due to the lack of soft water and permanent natural streams. Large daily and seasonal fluctuations of physicochemical parameters, such as extreme temperature, also play an important role in the survival of different species of fish [16].

After the creation of many reservoirs in the eighties, fish from Europe were introduced in order to increase and diversify fishery production in Tunisian reservoirs [17, 18]. According to Mtimet, Laouar and Mili et al., Mullet (*Mugil cephalus* and *Liza ramada),* Pike-perch (*Sander lucioperca*), Carp (*Cyprinus carpio*), Rud (*Scardinius erythrophthalmus*), Catfish (*Silurus glanis*), Eel (*Anguilla anguilla*), Tilapia (*Oreochromis niloticus*), Roach (*Rutilus rutilus)* and Barbel (*Barbus setivimensis*) represent the biggest catches in the reservoirs of Tunisia [10, 19, 78]. Losse et al. grouped freshwater fish into two categories: useful commercial species (Barbel and Eel) and valid commercial species (Carp, Pike-perch, Mullet and Catfish) [16].

We witnessed an important increase in production which raised from 843.5 T in 2000 to exceed 1204.6 T in 2018, with an exception of a decrease to 919 T in 2011. This decline is the result of the unstable political situation of the country and the lack of statistical data in this year (2011) [10]. Pisciculture practiced in freshwater bodies in Tunisia needs further support due to its major impact on inland areas economy and particularly on vulnerable fishermen earnings.

Despite several advocacy institutional efforts, the growing number of fishing licenses and fish population growth rate in freshwater bodies [21], levels of freshwater fish production remain low with 1300 T. Recent investigations have shown low fish catches in Tunisian reservoirs despite overall high density and biomass [12, 13, 21, 78].

Freshwater fish landing faces several issues, mainly the lack of well-founded data in relation with production statistics and general arrangements which are seminal for the growth of this activity [10, 76, 77]. While many studies have been conducted, information remains scarce in relation to the freshwater fish species status and distribution today which makes it difficult to study their biology traits and to manage their fisheries.

A new project entitled "*Population Status of Freshwater Fish in Tunisian Reservoirs*" started in 2013 in order to update the freshwater fish database for Tunisian reservoirs. A preliminary result, given a general information about freshwater fishes in Tunisian reservoirs, were presented by Mili et al. [10, 13, 14, 22, 23].

The current research work will be of great use to managers of fisheries since it aims to help improve productivity through the provision of details on the condition of fish cultured in freshwater and exploited in Tunisian reservoirs.

2 Material and Methods

2.1 Study Sites

With the exception of Sidi Saad Reservoir (35°22′53"N/09°41′42"E) which is located in the center of the country [24, 78] all the other 13 studied reservoirs are situated in the northern part of the country: Ghezala (37°03′12″N/09°31′43″E), Bouheurtma (36°40′19″N/08°47′18″E), Kekbaka (36°34′27″N/10°20′09"E), Bir Mcherga (36°30′41″N/10°00′37″E), Bezirekh (36°43′16″/10°37′57″E), Kasseb (36°45′41″/9°00′09″E), Laabid (36°49′13″N/10°42′11″E), Mallegue (36°18′51″N/08°42′08″E), Mlaabi (36°49′44"N/10°59′07"E), Sidi Barrak (37°01′29″N/08°56′11″E), Sidi Salem (36°35′27″/9°23′51″E), Seliana (36°09′11″N/09°22′13″E) and Lahjar (36°50′18″ N/11°02′ 37″E).

The minimum depth of dams varied from 12 m in Mlaabi Reservoir to 65 m in Mellegue Reservoir (Fig. 1; Table 1). These waterbodies are responsible for the irrigation of farmland near dams, whereas Sidi Salem, Bouheurtma and Sidi Barrak are also used for drinking in addition to the irrigation of the surrounding land [24].

Table 1 The fishing effort used and hydrological characteristics for the studied Tunisian reservoirs (Mili et al. 2020)

Reservoirs	Total surface of benthic gill nets (m^2)	Total surface of pelagic gill nets (m^2)	Depth (m^2)	Area (ha)
Bakbeka	720	480	17	102
Bir Mcherga	1440	480	43	705
Bouheurtma	1440	480	44	800
Bezirekh	720	480	11	102
Ghezela	720	480	20	122
Kasseb	1440	720	12	437
Laabid	720	480	14	120
Lahjar	720	480	13	250
Mellegue	1440	720	65	1280
Mlaabi	720	480	12	100
Sidi Barrak	1920	720	27	2734
Sidi Saad	1920	480	46	1700
Sidi Salem	3240	720	24	5760
Seliana	1440	480	19	600

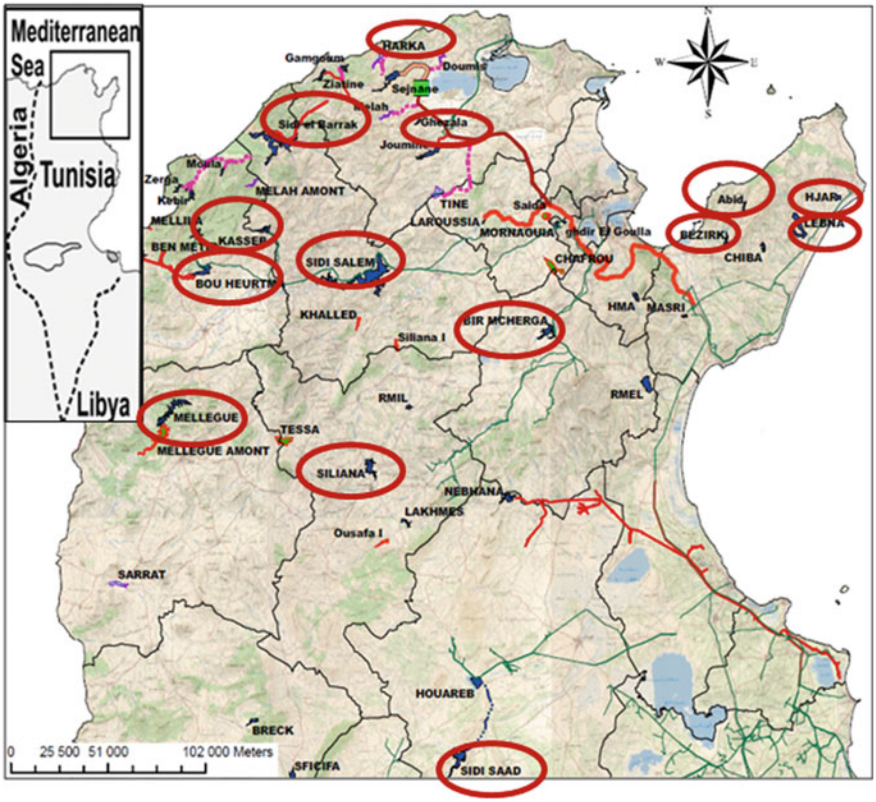

Fig. 1 Locations of the most important Tunisian reservoirs (modified by Mili et al. 2016)

2.2 Sampling

For fish sampling, we followed the European norm for the investigation of water quality sampling of fish which recommends the use of multi-mesh gill nets (EN 14,575 amended) [20, 25, 78]. Fishing operations using multi-mesh gill nets were made in 14 reservoirs (Sidi Saad, Seliana, Bekbeka, Kasseb, Bezirekh, Laabid, Mlaabi, Sidi Barrak, Lahjar, Sidi Salem, Ghezala, Bir Mcherga, Bouheurtma and Mellegue). Specimen were collected from these freshwater bodies as follows: in May 2013 from Ghezala, Lahjar and Bekbaka; in May 2014 from Bezirekh, Laabid, Mlaabi, Sidi Barrak and Sidi Salem; in May 2015 from Kasseb, Sidi Saad and Seliana and in May 2016 from Mellegue, Bouheurtma and Bir Mcherga. The month of May was chosen because during this time water temperature in Tunisian reservoirs is commonly over 15 °C and most fish species living in these freshwater bodies do not spawn at this time of the year [11]. A stratified random sampling design was applied in order to cope with the irregular distribution of fish species [13]. Different strata were identified in the sampled reservoir and specimen were collected at every stratum. Benthic types of fish were sampled using multi-mesh gill nets made for the purpose with 20 m length and 1.5 m depth. The meshes we used were of different sizes with 18 to 80 mm knot to knot, following a geometric series. Gill nets used to collect samples of pelagic fish were of 20 m length by 6 m depth. Thread diameter ranged between 0.23 and 0.28 mm. The hanging ratio for all horizontal mesh sizes was 0.5 and it was of 0.71 for lateral ropes [13]. A sampling effort of 24 gill nets per night [25] was required in order to spot a 50% change in relative abundance. Species vertical distribution was interpreted to evaluate data gathered between the benthic and pelagic areas. Six depth levels were determined for catches with gill net (0–3 m. 3–6 m. 6–9 m. 9–12 m, 12–12 m, and > 20 m), with random samples collected at every level. Not to calculate abundance in relation to hours of net setting time; nets were regularly placed between 6 and 8 p.m. and removed between 6 and 8 a.m. with a standard fishing period of 12 h.

The whole area cover per night in every reservoir for benthic gill nets and pelagic gill nets was summarized in Table 1. While we set two benthic nets at every sampling station (gill net sets), we placed nets one by one in the pelagic area. Catches, indicated in number per unit effort (NPUE), and biomass (weight per unit effort (WPUE)) were counted for every reservoir. NPUE and WPUE for gill nets are indicated per 1000 m^2 net surface and for a fishing time of 12 h according to EN 14,757 [25]. The fish captured during the gill net-fishing surveys were numbered, identified, counted, weighed (to 1 g accuracy) and measured for total length (TL to nearest 1 mm).

2.3 Data Analysis

We conducted Redundancy analysis (RDA) for fish abundance data in order to determine the structuring effects of depth strata and sampling sites, as well as the impact of the varied reservoirs. We also normalized fish abundance values before analysis.

The main structural parameters of the fisheries assemblage determined at each reservoir are specific richness S (number of species), abundance A (number of individuals/1000m^2), the Shannon–Wiener index H′ [26] and Pielou's evenness J' [27]. They were defined using the PRIMER v6 package.

The most abundant size class of each species was identified by using generalized additive model (GAM) [28]. GAMs are increasingly used in marine ecology and may be considered as a nonparametric generalization of linear regressions. We assessed Model validation as stated in Züur et al. [29] and we used R 2.15.0 [30] with the R packages of "Vegan" [31], "Pgirmess" [32], and "mgcv" to realize the statistical analysis and graphic display [28].

3 Results

3.1 Species Composition

Eight freshwater fish species were caught via the sampling protocol, using multi-mesh gill nets [25, 78], in the Tunisian reservoirs. The species caught in the prospected reservoirs are summarized in Table 2. A sum of 3654 fish were caught while collecting samples, with a heterogeneous distribution noted in the 14 reservoirs investigated. In Mellegue, 828 fish were caught, whereas only 6 fish were captured during a prospection survey made in Mlaabi. Cyprinid (Roach) species were the most numerous fish caught (Table 2). Gill net catches both in the benthic and pelagic areas were heavy in the epilimnetic water layer with improved species diversification. Only two native species of freshwater fishes are caught in the surveyed reservoirs: Barbell (*Luciobarbus callensis*) and Phoxinel (*Tropidophoxinellus callensis*). The Goby (*Pomatoschistus marmoratus*) seems to be absent in Tunisian waters. *Tropidophoxinellus callensis* was present only in Sidi Salem Reservoir and it was extirpated from Bouheurtma, Sidi Saad and Bir Mcherga according to the data given by Loss et al. [1]. However, *L. callensis* was captured in eight reservoirs (Table 2).

The specific richness (S) and the abundance (A) show a wide range of spatial–temporal variability, from 828 (Mellegue Reservoir in 2016) to 6 (Mlaabi Reservoir in 2014) ind/1000 m^2 of net; for abundance (Fig. 2), 2 (Kasseb Reservoir in 2015, Bir Mcherga Reservoir in 2016 and Mlaabi Reservoir in 2014) to 6 (Sidi Salem Reservoir in 2014) taxa for specific richness (Fig. 2). The Shannon index (H') also fluctuates and is generally low; it varied between 0.26 at Kassab Reservoir in 2015 and 1.66 bits./ind at Siliana Reservoir in the same year. The other values did not exceed 1.5 bits./ind (Fig. 2). Whereas, the evenness (J′) showed a significant increase from 0.1 to 0.99 (Fig. 2). This investigation made shows an alarming decline of stocks of Autochthonous freshwater fishes associated with a poor fish diversity in Tunisian reservoirs.

3.2 Fish Species Dynamics

Fish abundance varied remarkably between one depth stratum and another (RDA, $F = 3.51$, $p < 0.05$), sampling site (RDA, $F = 14.31$, $p < 0.001$), and when types of nets changed (RDA. $F = 2.47$, $p < 0.05$). The changes in fish abundance of 53.42% on the RDA can be explained by these factors, which shows an important impact on the variability ($p < 0.05$). Actually, when there was no Barbel, Rudd and Roach represented the most important prey, in terms of number, for Pike-perch. The study found that these types of fish highly correlated, indicating similar behavior; their correlation with the sampling zone near the dam was also substantial.

However, we were unable to define fish-size variance depending on the depth of layers and dam through the number of the captured fish. As for depth of layers, we

Table 2 Specific catch and biomass of freshwater fish expressed, respectively, as number per unit effort (NPUE) and weight per unit effort (WPUE) in 14 Tunisian reservoirs (Mili et al. 2020)

Reservoirs	Species	NPUE (Fish/1000 m^2)	WPUE (Kg/1000 m^2)
Bekbeka	Roach	33.33	2.07
	Pike-perch	4.17	0.40
	Mullet	6.94	1.84
	Carp	8.33	1.60
	Total	52.78	5.91
Bir Mcherga	Barbel	159.09	0.03
	Carp	126.77	0.01
	Total	285.86	0.04
Bouhertma	Roach	34.52	1.36
	Rudd	1.19	0.12
	Barbel	1.19	0.22
	Pike-perch	1.19	0.37
	Mullet	1.78	0.61
	Total	39.88	2.69
Bezirekh	Roach	39.16	3.30
	Rudd	89.16	8.53
	Pike-perch	2.5	1.41
	Mullet	2.5	0.87
	Total	133.33	14.10
Ghezala	Roach	30.00	1.16
	Mullet	7.50	1.61
	Barbel	6.67	1.75
	Pike-perch	0.83	0.09
	Total	45.00	4.32
Kasseb	Barbel	24.62	4.97
	Pike-perch	1.14	0.34
	Total	62.52	5.31
Laabid	Rudd	25.00	2.92
	Mullet	4.17	0.41
	Pike-perch	0.83	0.08
	Total	30.00	3.41
Lahjar	Roach	194.17	23.31
	Mullet	26.67	5.96
	Pike-perch	23.33	4.62
	Carp	4.17	0.61
	Total	248.33	34.51

(continued)

Table 2 (continued)

Reservoirs	Species	NPUE (Fish/1000 m^2)	WPUE (Kg/1000 m^2)
Mellegue	Roach	408.33	12.94
	Mullet	15.1	2.58
	Barbel	3.64	0.26
	Pike-perch	3.64	0.28
	Total	430.72	15.51
Mlaabi	Roach	3.33	0.39
	Rudd	1.67	0.15
	Total	5.00	0.54
Sidi Barrak	Barbel	45.83	14.19
	Pike-perch	1.25	0.44
	Mullet	6.66	3.55
	Total	53.75	18.17
Sidi Saad	Mullet	90.78	15.86
	Barbel	8.87	1.06
	Carp	7.09	0.94
	Roach	6.38	0.32
	Rudd	1.06	0.07
	Total	114.18	18.25
Sidi Salem	Roach	91.92	3.93
	Pike-perch	15.66	1.33
	Rudd	32.58	1.77
	Carp	1.52	0.53
	Phoxinel	3.03	0.10
	Mullet	0.76	0.48
	Total	145.45	8.13
Seliana	Mullet	50.00	7.59
	Barbel	2.50	0.14
	Carp	1.25	1.83
	Rudd	85.42	7.01
	Pike-perch	71.67	15.90
	Total	210.83	32.46

noted an obvious connection ranging from (0–3 m) for most of the fish. Additionally, the great part of freshwater fish appears to be more present in the 3–6-m and 6–9-m ranges. Fish caught by the pelagic nets have RDA scores close to those captured by the benthic nets. However, it was noted that productivity was more important when using the benthic nets.

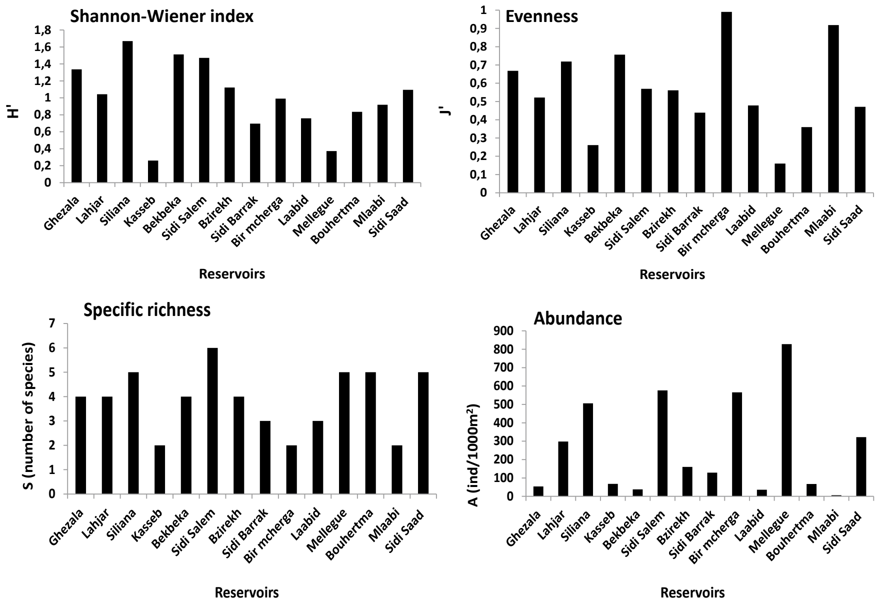

Fig. 2 Spatial and annual variability of the principal freshwater fish parameters in Tunisian reservoirs (S: specific richness; A: abundance; H′: Shannon–Wiener index; J′: evenness). (Mili et al. 2020)

In order to maintain sustainability and development of fish farming in Tunisia, we need to supply the reservoirs with Mugilidae. Coastal water presents high interest due to the seasonal abundance of the juveniles and fry of Mugilidae which are used for stocking freshwater reservoirs [1, 78]. Nowadays, the Technical Center of Aquaculture (CTA) regularly captures Mullets fry near the mouths of major Tunisian rivers. Mili et al. [33] analyzed the periods of the presence of Mullet fry along the Tunisian coasts. These authors demonstrate that fish-stocking density depends on food availability, carrying capacity, fish size and environmental conditions. It is also necessary to take into account the potential losses by mortality and predation. The number of stocked fries changes from one season to another, based on abundance in the fishing areas [33]. It has been noted when analyzing the collection of Mullet fry in the different stations that fry abundance is important during small periods.

The quantity of mullet fry collected is related to years. The objective of the Technical Center of Aquaculture is to attain 10,000,000 fries of mullet, as recommended by Losse et al. [1], but this quantity has never been reached.

Furthermore, *L. callensis* and *T. callensis* show an alarmingly stock status. Their biomass distribution is governed by depth and they are found mostly in downstream waters [15].

3.3 Vertical Distribution

As we can see in Fig. 3, a high connection between the 0–3 m stratum and fish species is observed. Catches of fish species were variably distributed within the sampled depth strata (0–3 m, 3–6 m, 6–9 m, 9–12 m, 12–20 m and > 20) (RDA, F = 2.47, $p < 0.05$). Harvest was the greatest (42.29% of total) at the 0–3 m stratum, followed by the 3–6 m (30.55%), the 6–9 m (18.23%) stratum, the 9–12 m (0.21%) stratum, the 12–20 m (7.84%) stratum and it was the lowest when depth exceeded 20 m (0.85%) (Fig. 3). Roach represented the biggest catch in the different strata of the Tunisian reservoirs (Fig. 3).

While we observed a heavy abundance of Mullet when captured at a depth below 9 m, no samples of Pike-perch could be collected at this depth (Fig. 3). Rudd and Barbel are present in all depth strata. The fish inhabiting the reservoirs under study are mostly present in the 0–20 m strata, but with much greater abundance in the upper layers. (RDA, F = 2.47, $p < 0.05$). Figure 3 shows that no specimen was caught at a depth exceeding 20 m, in any of the reservoirs. Catches of fish species differ significantly between strata (RDA, F = 2.47, $p < 0.05$) with higher abundance in the superficial strata (0–3 m).

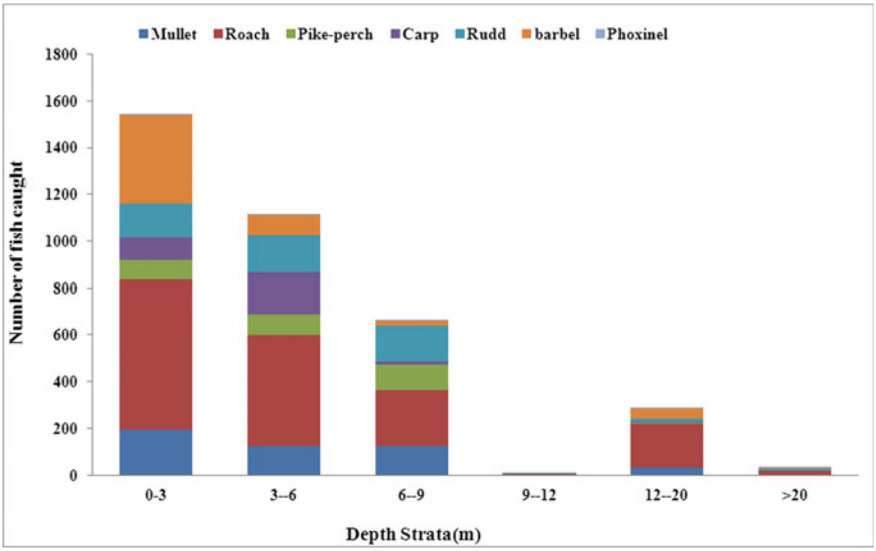

Fig. 3 Distribution of catches in Tunisian reservoirs (Mili et al. 2020)

3.4 General and Specific Abundance

Much more Roach (1865) than Barbel was captured (538), followed by Mullet (481), Rudd (478), Carp (292), and Pike-perch (285). This was observed in all Tunisian reservoirs with only 12 specimens of phoxinel caught in Sidi Salem Reservoir (RDA, $F = 10.14$, $p < 0.001$) (Fig. 4).

Numerical percentages of Roach caught were 43% followed by Barbel (15%), Mullet (13%), and Rudd (13%), respectively. Percentages for Carp and Pike-perch were 8% (Fig. 4). Yields (catch per unit effort, CPUE) by a number of *L. callensis* did not exceed 50 fish/1000 m^2 of nets except for Bir Mcherga Reservoir where its predator (*Sander lucioperca*) was overexploited (Fig. 4). Furthermore, the decline of the stocks of *T. callensis* and *L. callensis* can be explained by the introduction of carnivorous fishes, especially Pike-perch (*Sander lucioperca*) and Catfish (*Silurus glanis*).

The numerical yield of the total freshwater fish NPUE (fish/1000 m^2) was higher in Mellegue and Bir Mcherga than in Lahjar, Seliana, Sidi Saad, Bezirekh and Sidi Salem (Fig. 5). However, it was much lower in the other reservoirs (RDA, $F = 13.24$, $p < 0.001$). Catch rates by weight WPUE (kg/ 1000 m^2) were important in Lahjar and Seliana, medium in Sidi Barrak, Sidi Saad, Bezirekh, Sidi Salem and Mellegue (Fig. 5), and poor in the other reservoirs (RDA, $F = 14.62$, $p < 0.001$).

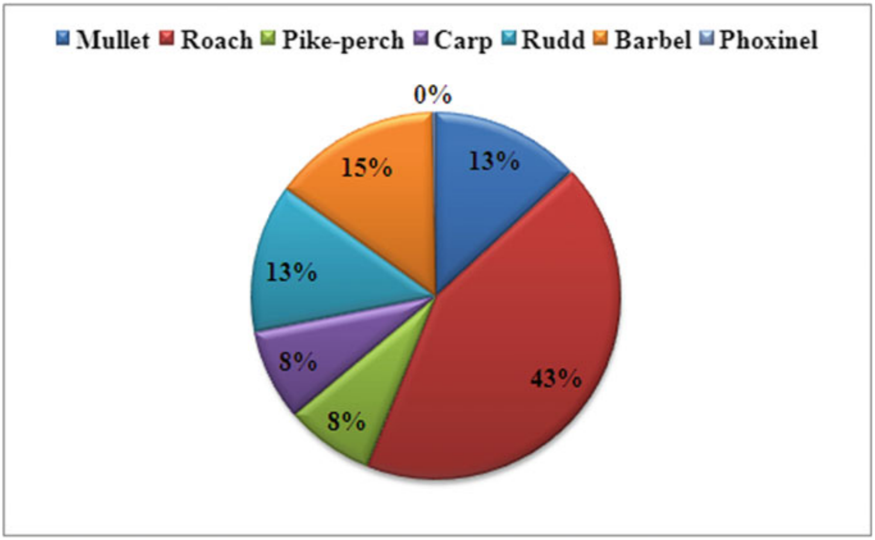

Fig. 4 Relative numerical abundance of fish in Tunisian reservoirs (Mili et al. 2020)

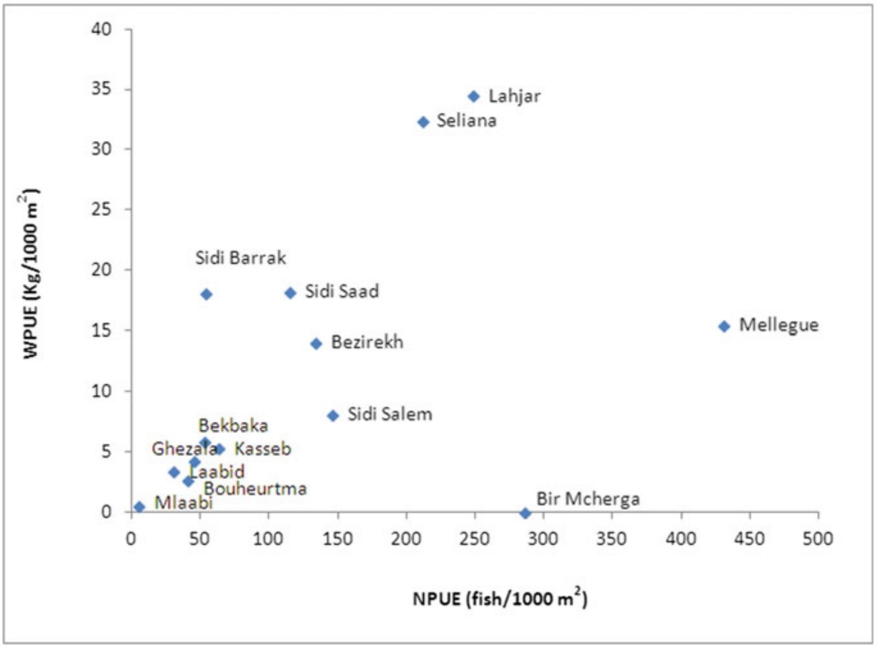

Fig. 5 Catch and biomass freshwater fish relationship in Tunisian reservoirs (Mili et al. 2020)

3.5 Population Structure

The caught Roach and Rudd had sizes varying from 12 to 30 cm and from 12 to 34 in Tunisian reservoirs, respectively (Fig. 6).

A considerable nonlinear relationship was noted between Rudd and Roach abundance and the different species sizes (GAM, $F = 23.2$, $p < 0.001$; Fig. 7). The covariate (size) accounted respectively for 82% and 81% of the deviance in variability for Roach and Rudd. The plot (Fig. 6) shows that Roach abundance is high in 17–24 cm size class and between 14 and 25 cm size class for Rudd. The use of several small meshes in the sampling survey led to heavy abundance of catch, while the biomass was fairly modest. Both Rudd and Roach which were caught were bigger in size than the one they reach during sexual maturity, which in this species, ranges from 11.92 to 12.48 cm, and it is attained when they are 1 year-old [79]. In all Tunisian reservoirs, the collected samples represent two age groups. The juvenile stages were absent in catches given the fact that the minimum mesh size used is 18 mm. Rudd and Roach seem to have found adequate situations to complete their life cycle once used as forage fish within the Tunisian reservoirs. The smallest identified size of this species in some reservoirs could be the result of the recency of its introduction (2012 in Ghezala, Mlaabi, and Lahjar; 2014 in Mellegue and Bouheurtma). In this research, we identified Roach as the most plentiful species of the Cyprinidae families in Tunisian reservoirs.

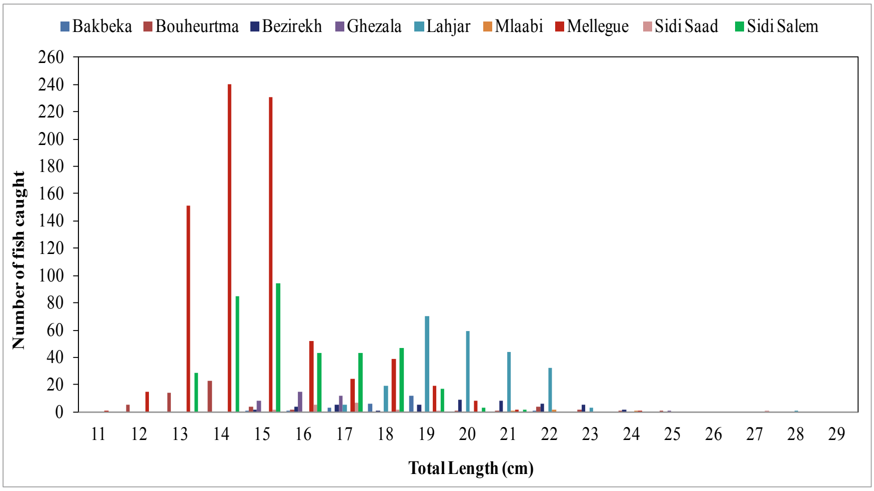

Fig. 6 Length-frequency distribution of Roach in Tunisian reservoirs. (Mili et al. 2020)

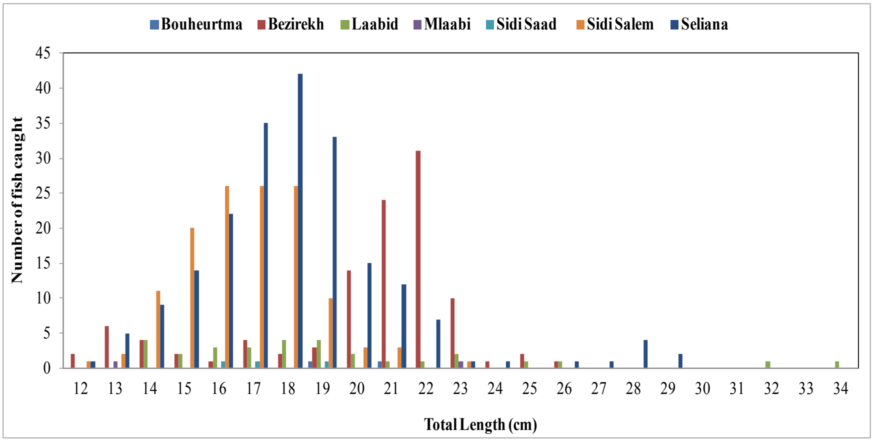

Fig. 7 Length-frequency distribution of Rudd in Tunisian reservoirs. (Mili et al. 2020)

Fish size in the Barbel catches ranged from 12 to 44 cm. The specimens of *L. callensis* captured in the 14 prospected Tunisian reservoirs allowed the identification of five age classes with lengths ranging between 12 and 44 cm. whereas no specimen was caught in Bakbeka, Bzirekh, Laabid, Lahjar, Sidi Salem, and Mlaabi (Fig. 8). A considerable nonlinear link was noted between the varied species sizes (GAM, $F = 4.41$, $p = 0.001$) and Barbel abundance. The covariate (size) presents a deviance in variability around 59%.

The plot (Fig. 8) accentuates high Barbel abundance in the 19–31 cm size classes. These populations mainly comprise juveniles. Natural mortality targets juveniles

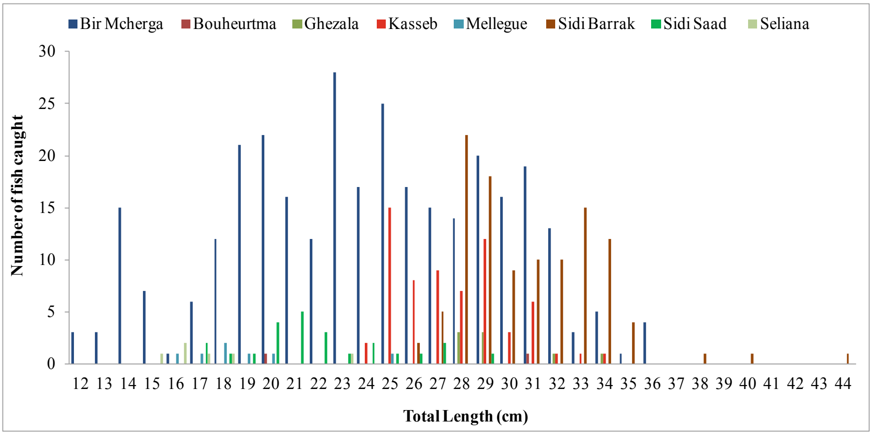

Fig. 8 Length-frequency distribution of Barbel in Tunisian reservoirs. (Mili et al. 2020)

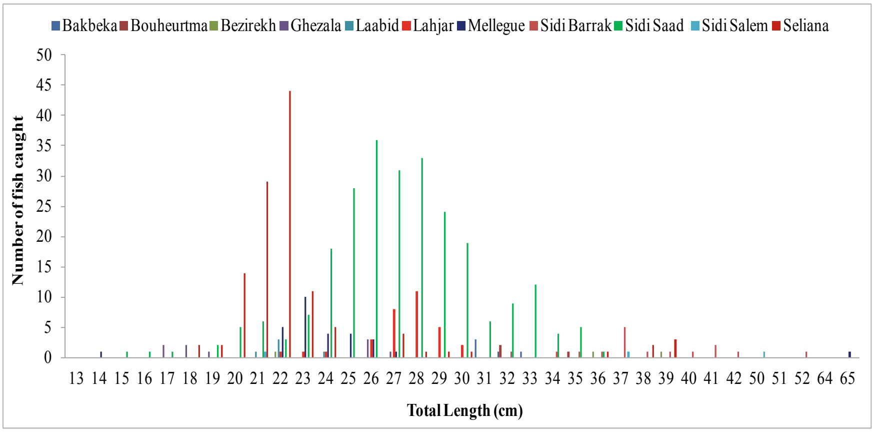

Fig. 9 Length-frequency distribution of Mullet in Tunisian reservoirs. (Mili et al. 2020)

most of the time, whereas fishing mortality targets adults [15]. The late sexual maturity for females (five or six years corresponding to 27.7 cm; [34] and the relatively low fertility (15,000 oocytes/female; [35]) are the main causes of the declines in stocks.

Fish sizes in the Mullet catches ranged from 14 to 65 cm in the prospected reservoirs (Fig. 9). In our study, the sampled population is composed of two- and four-years age group specimens in each reservoir. A significant nonlinear relationship was observed between the different species sizes (GAM, $F = 3.82$, $p = 0.01$) and Mullet abundance. The covariate (size) contributes to 73% of variability deviance.

The Fig. 9 shows that the most abundant size class of Mullet is 22–39 cm. Mullet is the most heavily fished species, representing the third of the total freshwater

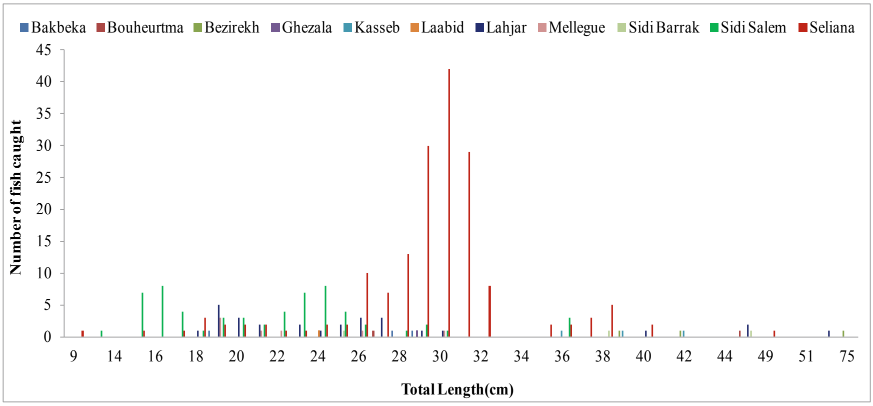

Fig. 10 Length-frequency distribution of Pike-perch in Tunisian reservoirs. (Mili et al. 2020)

fish production in Tunisian reservoirs. Physicochemical characteristics of water and trophic conditions seem to be in favor of Mullet growth in Tunisian reservoirs. Shoreline zones, which are not deep and that we did not investigate using nets, are rich in young fry. To maintain sustainable development of freshwater fish farming in Tunisia, reservoirs have been supplied with Mugilidae fries that were collected from coastal and estuaries areas after a short adaptation period with an optimum density based on reservoir's volume.

Fish size in the Pike-perch catches ranged from 9 to 75 cm in the 14 prospected Tunisian reservoirs, whereas no specimen was caught in Ghezala and Laabid (Fig. 10).

The nonlinear relationship observed between different species sizes (GAM, $F = 3.73$, $p = 0.001$) and Pike-perch abundance is significant. The covariate (size) represents 81% of variability deviance. The plot (Fig. 10) indicates that Pike-perch abundance is high in the 23–45 cm size classes. Altogether three age classes of Pike-perch were caught in the Tunisian reservoirs. Most samples (87%) were adults since they surpassed the age of sexual maturity which they attain when they turn one year old with a length of 24 cm and a weight of 90 g [36]. We can explain the spareness of Pike-perch samples in some Tunisian reservoirs with the recency of its introduction; this species was stocked in these reservoirs in 2012, except for Sidi Salem, Lahjar and Seliana reservoirs [10].

Fish sizes in the Carp catches ranged from 11 to 55 cm in the prospected reservoirs (Fig. 11). In our study, the sampled population is composed of four age groups in each reservoir. The nonlinear relationship observed between Carp abundance and the different species sizes is significant (GAM, $F = 2.65$, $p = 0.001$). The covariate (size) accounted for 63% of variability deviance.

The Fig. 11 shows that the most abundant size class of carp is 22–35 cm. The physicochemical characteristics of water and trophic conditions seem to be favorable for Carp growth in Tunisian reservoirs. However, the stock biomass of this species appears to be overexploited in the prospected reservoirs.

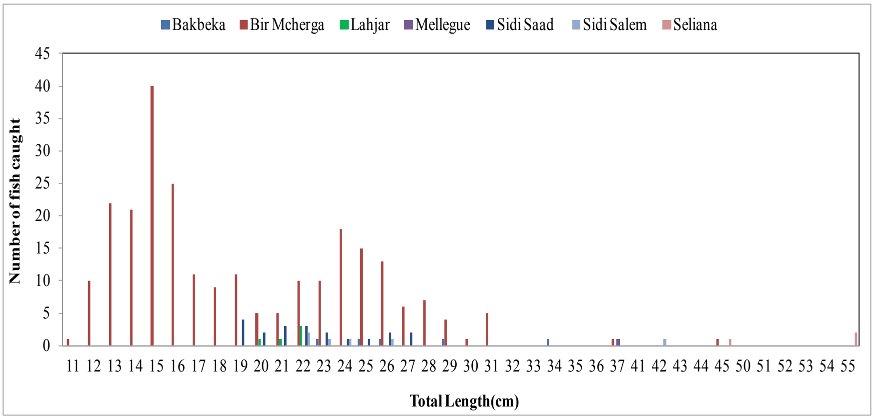

Fig. 11 Length-frequency distribution of Carp in Tunisian reservoirs. (Mili et al. 2020)

Fish sizes in the Phoxinel catches ranged from 13 to 16 cm in Sidi Salem Reservoir, whereas no specimen was caught in all other Tunisian reservoirs. Additionally, no significant effect of size class on the Phoxinel abundance was detected.

4 Discussions

Although several research works have investigated freshwater fish biology in Tunisian reservoirs [8, 11, 35–42, 78, 79] little information concerning the population status, distribution, and abundance of freshwater fish is available. The freshwater fish community in the Tunisian reservoirs seems to be characterized by the same structure mainly with Roach, Mullets, Barbel, Rud, Common Carp, Pike-perch and Phoxinelle.

Data collected in this study show that the structure of the fisheries assemblage in the Tunisian reservoirs has undergone significant changes. The species richness and the abundance show a significant difference between reservoirs with maximum record in Mellegue Reservoir with 784 individuals of Roach (*Rutilus rubilio*) and minimum record in Ghezela and Laabid Reservoirs; 1 individual of Pike-perch (*Sander lucioperca*) in 2013 and 2014 respectively. This variation can be attributed to environmental parameters and to the species biological cycles which are linked to the cyclic fluctuations of the climatic factors [43, 44]. Additionally, the fishing effort can be the most important cause of this variability. Jespersen et al. [45] reported that the total catch of freshwater fish-decline as the concentration of nutriments rise. Moreover, the lack of introduction of brood stock and fry fish, which coupled with the increase of the IUU fishing, resulted in the decrease of the number of species and fish productivity in Tunisian reservoirs [22, 23].

The various biotic indices used show a certain degree of inter-correlation. Indeed, the Evenness (J') classify the reservoirs of Ghezala, Bekbeka, Bir mcherga and

Mlaabi as reservoirs with good ecological status and more balanced community. Nevertheless, the change in H' was greater, which indicates poor ecological status in all reservoirs. H' is different, because it is a structure index based on specific dominance without taking into account the ecological affinity of species [46, 47].

Freshwater fish biomass distribution and the difference observed between size-classes appear to be influenced directly by many factors, such as reservoir morphometry (area and depth) and water quality. Abundance and biomass are influenced by fish density and eventually by the trophic status of the sampled reservoir [48]. Mehner et al. indicate that lake morphology and geographical position are important determinants of fish assemblages [47]. The study conducted in Lake Balaton (Hungary) demonstrates that the majority of variances in the gill net catch-per-unit-effort data are linked to water transparency which can impact the use of gill nets in two ways: visibility is affected as fish is more likely to be entangled in the net in turbid water than in clear water [49]. In addition, fish activity can change due to light intensity, being very high in low light, but low in darkness [49]. The size structure of bottom-fish species was connected to environmental gradients [50]. Mehner et al. indicate that fish community composition has been proven to be determined essentially by chlorophyll a content, maximum and mean depth, and reservoir volume [51]. Fish distribution has rarely occurred at random in their habitats; Fish are usually spread according to specific factors: the physical (habitat), along with historical and chemical problems of environmental status [52–54]. Moreover, biotic interactions suchlike competition in a reservoir can play a major role in changing fish distribution [51, 55]. As observed in this study, a clear effect of water quality on the fish species composition was noted, while no considerable impact of water quality on overall fish abundance or diversity was detected in Spanish reservoirs [56]. Carol et al. demonstrate that different types of fish can cope with ecological deterioration and that fish abundance and variety does not necessarily depend on water quality in freshwater habitat. For instance, fish abundance in Tunisian reservoirs was low, as a result of recent artificial introduction of the majority of species [10, 76–78]. A similar result is found, in European reservoirs, indicating that the majority of fish were captured in the surface layer (0–1.5 m) [57]. Vasek et al. reported that vertical distribution of fish in European reservoirs and the analyses of variation in gill net catches are impacted by day and night times; during the day, Roach gather mostly in the layer above the thermocline (3–4.5 m), but at night they move to the upward of the epilimnion (0–3 m). The distribution of freshwater fish biomass in Tunisian reservoirs is governed especially by depth [12]. According to the study conducted to asses fish biomass in Tunisian reservoirs [21], downstream fish density was more important than that in the middle and upstream layers. It was also observed that big fish occupy deep water while small fish dwell in shallow upstream areas. Additionally, this work demonstrates that densities change greatly between surface and deeper strata due to the spatial and temporal movement of fish populations with no clear behavioral tendencies [21]. Our findings corroborate with the study of Jeppesen et al. [45], which revealed similar distributional patterns. This was noted only in shallow reservoirs such as Bezirekh, Ghezala, Laabid, Lahjar and Mlaabi. A similar observation was obtained in several previous studies [58–62]. The deficiency of small fish in catch rates resulted from the absence of small mesh in our nets. Recent studies showed that fish density was negatively associated to maximum depth and that the increase in depth may result in greater predation risk [63, 64]. The same result is observed in Danish lakes where fish are concentrated in the coastal and benthic part of the upper two depth layers (0–6 m depth) [62]. Lauridsen et al. affirmed that the increase of abundances of Roach and Pike-perch, for instance, occurred in the littoral zones. Besides, many authors show that benthic and pelagic catches are the same in the epilimnetic stratum [65]. Achleitner et al. affirmed that the estimated pelagic biomass peaked near the thermocline, which was detected at a lower depth using hydroacoustics. Moreover, data related to size distribution indicates that capture of middle-sized fish was relatively more important when using gill nets than when using other fishing methods, for instance electrofishing [66]. Besides, the largest detected fish in the reservoirs under investigation were located close to the dam (i.e., downstream), but the smallest ones were found near the river (i.e. upstream). Fish of small size can benefit from better nutritional conditions, but the tributary location can perhaps be sought by some species inhabiting the Tunisian reservoirs (Pike-perch, Rudd, Roach and Barbel) in order to spawn [57, 68].

Similarly, the study made in Spanish reservoirs show that productivity of freshwater ecosystems and nutrient concentrations are higher within the river stream and that downstream are to be richer in nutrients [56]. Regarding reservoirs in this study, there is no information on water quality, but it has been suggested that waterbody become more eutrophic as they age. This has a direct impact on fish density with Barbel as the most prevalent in older reservoirs. Furthermore, several studies showed a clear difference in fish abundance between the pelagic and the benthic zones; the reservoir littoral zone had been found to be richer in nutrients than the central one. Alterations were detected in the fish community structure in relation with nutrient gradient [45, 69].

Gill nets used in 1991 in fishing test operation and fishery control were made in monofilament and multifilament with float line (floating 1.8 kg /100 m) and lead line (3.2 kg /100 m). Loss et al. used nine different mesh sizes: 15, 25, 32, 40, 50, 60, 70, 80, and 100 mm [1, 16]. The estimation of stocks and CPUE were made using multi-mesh gill nets in 1990 in Sidi Salem, Mellegue, Bir Mcherga, Nebhana and Lebna Reservoirs. This chapter showed that the annual average of numeric and weight CPUE of Mullet in Sidi Salem Reservoir are around 0.66 fish/gill net and 439 g/gill net, respectively. The reservoir of Bir Mcherga was repopulated with 800,000 of Mullets fry between 1985 and 1989 [70]. Important fishing activity in 1989 induced overexploitation of the stocks of freshwater fish in this reservoir. The electric fishing associated with multi-mesh gill nets allowed the estimation of the Mullets biomass before the overexploitation, which was evaluated at 6 kg/ha. Mullet numeric and weight CPUEs are 1.5 fish/gillnet and 428 g/gillnet, respectively [1].

The CPUE by numbers and weight decreased with increasing nutrient concentration. A recent study indicates that the percentage of piscivores fish is a water quality indicator [71]. Trophic and functional structure analysis shows that the majority of Tunisian reservoirs are strongly dominated by herbivores, represented by the group of Cyprinidae (39.77% of *Rutilus rubilio* and 12.12% of *Scardinius erythrophthalmus*) followed by detritivores (19.35% of Mullets). The potential piscivore fish biomass, including all size classes of Pike-perch, measured as a percentage of the total fish biomass indicates an imbalance in the food chain. The fish communities in Tunisian reservoirs are composed mostly of cyprinids as is the case in most lakes in France [48]. The presence of pelagic species populations can be better assessed by hydroacoustic surveys, due to the selectivity bias that occurs when using passive gear [48]. Benthic gill net fishing detected, on average, 93% of species and allowed the provision of the best representation of fish species in Tunisian reservoirs. Some species, for example the European Eel, and *A. anguilla* (L.), or the European Catfish, *S. glanis* L. are difficult to capture using gill nets due to their morphology, their preferred habitat in reservoirs or their behavior. Previous research has shown that pelagic gill nets, in contrast to benthic gill nets, are not able to bring mush data on species composition [48], which is consistent with the findings of the present study. Gill nets, which are highly selective, captured only actively moving fish because they are passive sampling gears. In addition, research has shown that gill net fishing is biased due to discrepancies in fish behavior, size, and activity [65]. Gill net surveys give reliable data on trends in fish density based on the CPUE, while gill nets do not allow stock estimations for the whole reservoir, and only a few comparisons of CPUE to real population density are possible to try [66]. Many authors suggest that the CEN standard will give an ambiguous picture of the proportion of different fish species in reservoirs [67]. The passive sampling method yields results impacted by methodological and environmental variables. The majority of fish species are active during the day and gather in shoals. In addition, gillnetting might be impacted by the timing of gill net sampling [68, 70, 72, 73, 75]. This means we should use gill nets carefully when analyzing fish abundance. When using multi-mesh gill nets for fish sampling, some considerations should be taken into account during data analysis due to the limitations associated with it. On the other hand, the use of multiple sampling techniques can offer an additional understanding of population characteristics by providing estimates of abundance in different species life history stages [20, 74, 75]. Besides, specific fishing gears can be used to compensate for deficiencies in fish population sampling [20, 74].

5 Conclusions

The diagnosis of the current situation in the freshwater fisheries in Tunisian reservoirs have brought several findings. Freshwater fishery management can help in handling several administrative and technical problems. However, well-founded fisheries statistics are badly needed in order to ensure the development of this activity. The landing statistics of freshwater fish have been criticized by scientists and by professionals. Therefore, unreliable statistical limits any study based on this data [10]. The failure to produce the required quantities of freshwater fish is due to the mismanagement of fisheries by fishermen. Additionally, in Tunisian reservoirs necessary data with regard to fish distribution patterns are not available [10]. This information is seminal for the improvement of our understanding of the stocks and for the adjustment of fisheries management [12]. Moreover inefficient control services are unable to handle the phenomenon of IUU fishing. This study corroborates with previous findings in that it shows poor diversity associated with an alarming decline in stocks of autochthonous freshwater fishes in Tunisian reservoirs.

The difficulty to communicate with fishermen leads to serious problems in all aspects of freshwater fisheries: marketing, stocking, purchase of equipment, etc.). Fisherman lack of skill in making fishing gears as well as the remoteness of outlets selling fishing equipment result in an increase in operating expenses as well as harvest gear low efficiency. Besides, the use of a non-regulatory mesh and the failure to comply with the allowed timing for fishing in most dams cause inappropriate exploitation of freshwater fisheries. In addition, the difficulty of marketing and the price of volatility mullet cause major problems for fishermen. These issues together with fisheries exploitation caused several problems in ecosystem structure. Moreover, the fish population in lakes is an important component of the ecosystem and might be beneficial through two major channels: their direct or indirect impact on water quality and fishery income.

It can be argued that Tunisian reservoirs have a great production potential thanks to their big capacity for fish breeding and the good growth rate of freshwater fish species. Since all the introduced species proved to have a good growth rate, development of freshwater fisheries should be sought.

6 Recommendations

In order to solve problems related to freshwater fisheries and to develop freshwater fish farming in Tunisian reservoirs, we suggest the following solutions:

– Evaluating the stocking success through the analysis of the freshwater fish growth increment;
– Increasing control over the types of fishing gears used with regard to the mesh size and the number of nets;
– Highly qualified authorities ought to enhance surveillance in order to limit IUU fishing (outside permitted fishing seasons and fishing without authorization);
– It is important to exert pressure, by adjusting the quantities of fingerlings stocked, when fishermen do not comply with regulations in fisheries;
– Standardizing the used fishing gear and types of nets and setting a specific fishing schedule for the year.
– Training fishermen in net making and in using the right gear for each type of reservoir.
– The exploitation of fish in reservoirs can be better if it is carried out by groups of fishermen.

We recommend also the exploitation of Tunisian reservoirs seeking the maximum capture of Pike-perch for export and Mullet for the Tunisian market. This will be achieved following the introduction of fry captured from the natural sites and transferred to reservoirs for stocking or produced in hatcheries. In order to enhance freshwater fish farming, it is of paramount importance to grant reservoirs to developers in the private sector and to create a freshwater fish hatchery [10].

To conclude, fishery management can be implemented through several kinds of operations: the introduction of fry fish species, making decisions regarding the total catch permitted, applying the legislative fishery regulations on a number of boats, determining the net mesh size to regulate the marketed fish size, and having fishermen comply with seasonal and site regulations. Fishery management implementation will have a positive impact on fishermen revenues and on water quality in the reservoirs.

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Conclusions and Recommendations

Updates, Conclusions, and Recommendations for "Agriculture Productivity in Tunisia Under Stressed Environment"

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Abstract This chapter aims to highlight the main conclusions and recommendations that can be extracted from the chapters contributed to this book. The first part includes a brief overview of some distinguished studies of main crops, in terms of the cultivated area especially olives, dates and cereals. It provides a board overview of some limiting factors of agriculture production in Tunisia such as climate change, pests, weeds and fertilizer application. Nevertheless, under scarcity conditions and climate change considerable efforts have been devoted by Tunisian scientific researchers over time to introduce policies to increase water efficiency based on the concept which states more can be achieved with less water through best practice management. In part 2, the scientific ground of this work is set by presenting different study cases dealing with sustainable use of irrigation water in arid areas. Part 3 considers the marine and terrestrial living environment with special reference to the fishery production system and the importance of Tunisian rangelands systems. The current chapter includes a set of recommendations for the future works that aim to get benefits from good agricultural practices toward the Tunisian stressed environmental.

Keywords Agriculture · Farming · Crop · Medicinal plant · Pest · Weed · Fertilizer · Water · Rangeland · Fishery · Management · Sustainability · Tunisia

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1 Update

"Agriculture is an important sector in Tunisia contributing with about 8.7% to the national Gross Domestic Product and employing around 16.2% of the total employment in the country" [1]. However, "Tunisia is also characterized by low rainfall and limited renewable water resources [2]. It is influenced by the arid and semi-arid climate that covers more than ¾ of its area" [3]. "The agricultural sector is also highly dependent on water resources since it consumes more than 75% of the total water use in the country" [4, 5]. Another major problem of the agricultural sector in Tunisia is the small farms' size. In fact, the average farm size in Tunisia in 2005 was only about 10.2 ha [5].

Agricultural productivity issues are generally well dealt with in agricultural policies. Therefore, productivity should be assessed with regard to the time spent by small-scale farmers and their families on their holding. However, family farming is the most common production system in Tunisia who plays a key role in supporting sustainable farming practices through enhancing farmers' technical performance as well as contributing to the environmental sustainability of farms. This chapter aims to evaluate the current situation and expectations for the future development of family farming in four different Tunisian provinces (namely, Jendouba, Zaghouan, Siliana and Kairouan). The study aims to analyze the farmer-environment relationship by estimating the technical and environmental efficiency with which family farms operate. Results of a survey conducted among 397 agricultural holdings specialized in the production of cereal crops allow deriving some important policy implications. Since there is considerable room to improve both technical and environmental efficiency, providing farmers with necessary information on how to adequately use chemical inputs may be expected to improve production performance [6]. More rational and less arbitrary use of chemical inputs would certainly reduce pollution and improve technical performance. This can be achieved through specialized extension and training services that transfer knowledge to farmers.

The olive tree is a major cultural crop in many countries around the Mediterranean Sea characterized by its tolerance to drought and salt. Its major role both in minimizing erosion and desertification effects, have as a result that olive cultivation is the main crop able to establish a sustainable system in subsistence agricultural areas. Nevertheless, in Tunisia more than 80% of olive orchards are located in semi-arid and arid conditions (center and south). That is why, efforts have been made notably by increasing tree density and even by shifting from rain-fed to irrigated conditions. Nowadays, the adoption of an appropriate technological package for each planting system (choice of variety, training system, pruning, irrigation, fertilization and pest control) is necessary to enhance the production and the profit of the grower.

There are more than 600 date cultivars in the world that differ in form, nutritional and organoleptic characteristics [7]. However, the Tunisian date palm is represented by more than 250 cultivars [8], which are unfortunately threatened by the expansion of *Deglet Nour* [9]. This chapter also provides an overview of the date palm fruit value

(Phoenix dactylifera L.) which is known over centuries, mainly the originality and its valorisation.

Rosa species, classified as Medicinal and Aromatic Plants, widely distributed in the Northern and Central of Tunisia who eight species: *Rosa gallica* L., *R. agrestis* Savi., *R. sicula* Tratt., *R. sempervirens* L., *R. stylosa* Desv., *R. micrantha* Sm., *R. moschata* Hermm. and *R. canina* L. [10] are found. *Rosa* species are known as aromatic and medicinal plants and characterized by their richness on phytochemicals able to exhibit several biological activities. This review aims to describe the Rosa species discrimination based on their geographic repartition, edaphic preferences, bioclimatic situations, plant communities, phytochemical compositions and biological activities. The edaphic characteristics differ according to the regions. The requirements of Rosa's species for soils are different. However, the bioclimatic stages for the spontaneous growth of these species are humid, subhumid or upper semi-arid. Those species need rainfall (more than 400 $mm.yr^{-1}$), and they are glycophytes. Only *Rosa agrestis* and *R. micrantha*, which the rainfall is less than 400 $mm.yr^1$, need humid soils situated in the watercourse of ravines. Thus, the floristic composition accompanying *R. canina*, *R. sepmervirens,* and *R. moschata* is very rich in species. The climatic conditions and edaphic characteristics are favorable for this biodiversity.

Land plants and insects have coexisted for more than 400 million years [11]. In co-evolution, both have evolved strategies to avoid each other's defense systems. Nevertheless, to limit the herbivores damages, they produce specialized morphological structures or secondary metabolites and proteins that have toxic, repellent, and/or anti-nutritional effects on the herbivores [12]. These metabolites are useful in plant defense against pathogens and insects' herbivores and their role in beneficial insect attraction such as pollinators and auxiliaries. The authors provide an overview of the diversity of secondary metabolites in Mediterranean plants and their multifarious biological functions in crop protection against pests. The secondary metabolites are classified into four different groups according to their biosynthetic origin: terpenoids, alkaloids and phenylpropanoids which each one was characterized with a specific mode of action against specific insects pests.

The phenomenon of biological invasions accelerated on a global scale in the latter half of the twentieth century [13, 14]. Some introductions have led to dramatic declines in native animal and plant species and the functioning of ecosystems [15]. However, Tunisia, as a signatory country of the Convention on Biological Diversity, is engaged to support the achievement of Target 9 related to the Invasive Alien Species and states that "*by 2020, invasive alien species and pathways are identified and prioritized, priority species are controlled or eradicated and measures are in place to manage pathways to prevent their introduction and establishment*" [16]. The author focuses on the biological invasion process and impacts of *Solanum elaeagnifolium* Cav. in Tunisia and presents the main components of an effective Invasive Alien Plants management scheme and proposes methods and tools that can be integrated into a national plan dedicated to the management of this weed.

According to the World Health Organization, 80% of the world's population uses medicinal plants to meet the needs of primary health care [17]. In recent decades, the focus has been on the adverse effects of the misuse of chemical fertilizers on soil health, human health and the environment. A research has been conducted in north-west of Tunisia to substitute mineral fertilization with the improved organic one (Biochar and compost) to obtain soil with good chemical, physical and biological fertility. Results indicate that the blocks fertilized by Biochar + compost are the richest in mineral nitrogen, potassium and phosphorus and organic matter. And good results have been found for inhibition of bacterial growth by methanolic extracts of Mentha spicata.

Agriculture, as the main consumer of freshwater, is currently faced with the challenge of a new approach to water resource management that ensures the protection of water resources and their integrity [18]. However, proper Irrigation water management is a key factor in increasing water use efficiency [19–21] particularly in Mediterranean climatic conditions [22]. The authors dealt with the water productivity of durum grown under semi-arid conditions. Relationships of grain yield, water use and water use efficiency were developed for wheat grown under semi-arid Mediterranean conditions. The STICS crop model was applied to assess crop yield and Water Use Efficiency of *durum wheat in the irrigated scheme of the Bouficha region,* taking into account the pedoclimatic variability in the study area. The statistical analysis did not reveal a significant effect of irrigation frequency on water use efficiency. This corroborates with the results reported by Pereira et al. [23]. Nevertheless, as indicated by Lasram et al. [24] WUE may decrease for the high applied amount of water. Indeed, WUE tends to decrease if the amount of water received by the crop exceeds almost 3500 m^3/ha.

In the Mediterranean semi-arid context and under the pressure of increasing water demand from one side and the climate change from the other side, water resources are shrinking and critical thresholds of water availability and quality are threatening the sustainability of many agroecosystems. This is the case of the irrigated orange production area of the governorate of Nabeul, Tunisia [25]. In this area, the adaptation capacity of the agroecosystem is limited by the lack of awareness about climate change challenges [26, 27], which is an important determinant of farmers and local stakeholders' pro-environmental behaviours [28]. This study attempts to understand the current institutional barriers to effectively disseminate new irrigation technologies in the Citrus Cap Bon production area and the essential measures to be taken to overcome barriers with regard to the keys to better water resource management through surveying the involved institutions.

Water stable isotopes have been used since the 61's as natural tracers of the hydrological cycle. Water entering a catchment has a characteristic fingerprint of its origin and therefore can help to identify where the water in the system comes from. In this chapter, a multicriteria approach in studying the hydrodynamics of a multilayer aquifer system has been conducted in the Mateur plain, Northern Tunisia. It aims to reconstruct the hydrogeological framework of the shallow and the two-deep aquifers distinguished in this area and then to define their hydrochemical and isotopic features. Physical and chemical parameters of groundwater such as electrical conductivity, pH, total dissolved solids, Na, K, Ca, Mg, Cl, HCO_3, SO_4, Sr and water molecule isotopes ($\delta^{18}O$, δ^2H and ^3H) were determined.

Climate change projections [29] reveal that the Mediterranean region will be particularly affected by the drier and hotter conditions combined to the decrease of the renewable water resources up to 50% within the next 100 years. In Tunisia, agriculture represents 80% of all water abstraction in the country and 74% of the total consumption for the sector coming from groundwater and inducing aquifers overexploitation of 26% of them at an average rate of 146% [30]. The study is conducted in the Cap Bon region northeastern Tunisia, where irrigation has increased in the past few decades, using intensively groundwater resources resulting in their degradation as well as their conflicting uses. Then, the Global Water Footprint (WF) Standard approach has been used to calculate the volumetric blue and green water footprint related to wheat, tomato and citrus production as major crops in the region. The average of total WF of crop production was about 1821 Mm^3/yr (85% green, 15% blue) over the period 1999–2008. The total WF (green + blue) averaged 131.28 m^3/ton of tomato and 445 m^3/ton of citrus crop. The green WF per ton of wheat (1670 m^3/ton) obtained in this study is equal to the world average (1620 m^3/ton). The development of irrigated agriculture, and significant improvements in blue WF induced a large pressure on water resources.

In Tunisia, rangelands contributed by 65% in the sixties, but in the last decade, contribution regressed to 10–25% [31, 32]. Therefore, farmers use more and more intensive and semi-intensive systems for growing and fattening lambs [33]. A synthesis of data concerning growth performances, carcass traits and meat fatty acid composition of lambs produced on different rangelands of the arid and semi-arid regions of Tunisia was presented in this chapter. Lambs reared on rangeland or indoor, with concentrate supplementation have the same Average Daily Gain and carcass performances. However, the carcass produced on the rangeland was less fatty. Moreover, meat lamb produced on rangeland was more dietetic because of lower intramuscular fat, lower level of the Monounsaturated Fatty Acid and a higher level of Polyunsaturated Fatty Acid.

Freshwater fish farming is a relatively recent activity in Tunisia which had been started in the sixties [34]. The research was conducted in order to monitor and assess the state of Tunisian freshwater fisheries shows that the most important Yields by number and by Weight are obtained in the Lahjar reservoir (446.43 fish/1000 m^2 of nets and 28.75 kg/1000 m^2 of nets). However, the Mlaabi reservoir represents the poorest reservoir in Tunisia. The Catch Per Unit Effort in this dam does not exceed 6.25 fish/1000 m^2 of nets and 0.67 kg/1000m^2 of nets. The Shannon index (H') and evenness (J') classify the 14 Tunisian reservoirs in the bad ecological status (H' < 1.5) inducing the presence of imbalanced structure which means that the community of the freshwater fisheries was dominated by a small number of species (generally one species of cyprinids).

2 Conclusions

Overviewed chapters which deal about cereal, olive and date palm trees emphasize the importance of cultural practices based on a good understanding of the natural environment and all its soil, climatic, agronomic, biological and social component parts and their possible interactions. Studies show the importance of the promotion of new olive and date products valued by consumers in Tunisia and improve the performance of decision-making units for enhancing cereal productivity, which in turn reduces the large deficit between domestic needs and production and ensures food security.

However, the study of the biochar amendment effect on the physicochemical properties of a soil cultivated in green mint (Mentha viridis L.)" concluded that the organic fertilization can be a solution to improve the quality of aromatic and medicinal plants and the quality of methanolic extract and at the same time serves to reduce the impact of chemical fertilization. As another enemy of crops, research show in this book reveal to better succeed *Solanum elaeagnifolium* control the species bioecological attributes and recommendations concerning its chemical and mechanical control as well as their appropriate application times should be integrated on a specific management program to thrive its eradication in the newly infested area and its control and containment in densely infested areas.

In the field of sustainable agriculture and water management, different case studies are presented in this book. The research related to improving the water use efficiency of Durum Wheat in Tunisian semi-arid conditions" emphasizes that a policy for maximizing yield should be avoided under limited water resources conditions. In North Tunisia, the work done using water isotopes for sustainable management of agricultural water indicates that water chemistry is regulated primarily by the combination of three processes: (1) weathering of minerals such as silicates and calcites; (2) ion reverse exchange with host rocks, and (3) mixing with Cl-rich water from the Lake Ichkeul. Water isotopes applied as a management tool helped to identify the origin of degradation risk of a multilayered aquifer situated in a high farming region. In the same region, the assessment of blue and green water resources sustainability for crop production has concluded the need for a better assessment of green water needs for the sustainability of the agrosystems.

For the breeding sector, more precisely, in the chapter dealing with producing Barbarine lambs on Tunisian rangelands conclusion show that the type of rangeland has a significant effect on the n-3 PUFA, with a higher level for natural shrubs rangeland. Improving rangeland quality and management could be a solution to improve productivity. Freshwater fish farming in Tunisian reservoirs presents several technical and administrative problems. Authors conclude that most of these reservoirs especially require support actions to improve fish productivity and population status such as increasing the control on fishing gear and the introduction of broodstock and fry fish.

3 Recommendations

Different recommendations have been concluded per each chapter mentioned in "Agriculture productivity in Tunisia Under Stressed Environment" book.

1-Implementation of a strategy based on efficient use of scarce resources as well as "polluting" inputs is especially relevant in the Tunisian cereal sector.
2-The quality of Tunisian oil can be enhanced and valorized by adopting good harvesting conditions, efficient processing methods, adequate packaging, development of products with the protected designation origin and Protected geographical indication.
3-The identity of Tunisian date cultivars must be valorized by proposing new ways of valuing sorting gaps and declassed cultivars in order to minimize losses and expand the range of byproducts of dates.
4-The conservation of Rosa Species in Tunisia should be a priority in the development plans and its seeds must be preserved in the National Gene Bank.
5-There are several solutions for integrated pests management in Tunisia, including the use of the secondary metabolites as a geochemical approach.
6-*Solanum elaeagnifolium* is a very important invasive plant in irrigated zones in Tunisia, so the integrated management approach has a benefic role in eradicating the infested areas.
7-In order to improve the effect on the soil physiochemical properties, agronomists and farmers have to make combinations of organic practices such as the combination of biochar with seaweed or with coffee grounds.
8-For improving water use efficiency of cereals in Tunisian semi-arid conditions more research effort should be concentrated on links between effects of water regime with fertilization one.
9-Water policy must be based on the proactive approach and associated with the preparedness plans. However, the implementation of a Smart-administration with access to technology should support decision-makers. By the way, the use of multitracer methodology combining geochemical and isotopic approach as a decision system tools should play an important role in policy-relevant issues. Such the assessment of green water resource place in water resource investments.
10-Meat produced on rangeland could have a quality sign that would promote this product and keep this production system.
11-The appropriate measures that would improve marine fish farm status in Tunisia are increasing the control on fishing gear and conduct training on nets confection of fishermen.

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