La borsa di dottorato è stata cofinanziata con risorse del
Programma Operativo Nazionale Ricerca e Innovazione 2014-2020 (CCI 2014IT16M2OP005),
Fondo Sociale Europeo, Azione I.1 "Dottorati Innovativi con caratterizzazione Industriale"

UNIONE EUROPEA
Fondo Sociale Europeo

Ministero dell'Università e della Ricerca

PON RICERCA E INNOVAZIONE

UNIVERSITÀ DEGLI STUDI DEL MOLISE

INSTITUTO SUPERIOR DE AGRONOMIA
Universidade de Lisboa

Department of Agricultural, Environmental and Food Sciences

PhD Course
AGRICULTURAL TECHNOLOGIES AND BIOTECHNOLOGIES
(CURRICULUM: PLANT PRODUCTION AND PROTECTION)

CYCLE XXXIII

Discipline and Scientific Sector
Agronomy AGR/02

PhD Thesis

Development of a Solar Fertigation System for crop management using Environmental Forecast Analysis

Supervisor: Prof. Dr. Stefano Marino
Co-supervisor: Prof. Dr. Arturo Alvino
External Supervisor: Prof. Dr. Maria Isabel Freire Ribeiro Ferreira
Industrial Supervisor: Engr. Sergio Strazzella
Coordinator: Prof. Dr. Giuseppe Maiorano

Uzair Ahmad
162435

Academic Year 2020-21

La borsa di dottorato è stata cofinanziata con risorse del
Programma Operativo Nazionale Ricerca e Innovazione 2014-2020 (CCI 2014IT16M2OP005),
Fondo Sociale Europeo, Azione I.1 "Dottorati Innovativi con caratterizzazione Industriale"

UNIONE EUROPEA
Fondo Sociale Europeo

Ministero dell'Università e della Ricerca

PON RICERCA E INNOVAZIONE

UNIVERSITÀ DEGLI STUDI DEL MOLISE

INSTITUTO SUPERIOR DE AGRONOMIA
Universidade de Lisboa

Department of Agricultural, Environmental and Food Sciences

PhD Course
AGRICULTURAL TECHNOLOGIES AND BIOTECHNOLOGIES
(CURRICULUM: PLANT PRODUCTION AND PROTECTION)

CYCLE XXXIII

Discipline and Scientific Sector
Agronomy AGR/02

PhD Thesis

Development of a Solar Fertigation System for crop management using Environmental Forecast Analysis

Prof. Dr. Stefano Marino
Supervisor

Prof. Dr. Giuseppe Maiorano
Coordinator

Uzair Ahmad
162435

Academic Year 2020-21

Dedicated to my beloved Family.

If I ever try to find my beloved ones, or know the truth about what happened, at least I know that you will always be present in my thesis.

Acknowledgements

Being the first in my family to join a university, the program 'Innovative doctorates with Industrial and International characterization' was carried out with the financial assistance of National Operational Program on Research and Innovation. The project was funded by European Regional Development Fund of the Ministry of Education, University and Research (DOT1339335 – H39H18000160006).

I am extremely thankful to my supervisors, Prof. Dr. Stefano Marino and Prof. Dr. Arturo Alvino in the Department of Agricultural, Environmental, and Food Sciences at the University of Molise for their noble guidance, support, and enthusiasm. I am grateful to Prof. Dr. Giuseppe Maiorano, coordinator of the International Ph.D. in Agriculture Technologies and Biotechnologies, for his extended cooperation.

Very special thanks to Prof. Dr. Maria Isabel Freire Ribeiro Ferreira in the Department of Biosystems Science and Engineering at the Superior Institute of Agronomy Lisbon, who made me a learned one and guided me in research directions. Her company in field and laboratory will always be remembered. I would like to acknowledge her for providing me with her valuable suggestions in data analysis.

I would like to thank my departmental colleagues for assistance in different aspects, such as bureaucratic support and safe driving during the field work. I would never forget official staff for providing me a comfortable environment, room and computer during write up of my thesis, research and articles. Last but not least, I would like to thank all of my family members for motivating me all the time.

List of scientific papers during the PhD

1. Ahmad U, Alvino A, Marino S. Solar Fertigation: A sustainable and smart IoT based irrigation and fertilization system for efficient water and nutrient management. Agron. mdpi, 2022. ISSN 2073-4395, Cite score: 2.6 © 2022 Agronomy. Impact factor: 3.417. Submitted

2. Ahmad U, Nasirahmadi A, Hensel O, Marino S. Technology and data fusion methods to enhance site-specific crop monitoring. Agron. 2022; 12(3), 555. February, 2022. e-ISSN: 2073-4395 © 2022 Agronomy mdpi. Impact factor: 3.417. Citescore: 2.6 Scopus.

3. Ahmad U, Alvino A, Marino S. A Review of Crop Water Stress Assessment Using Remote Sensing. Rem. Sens. 2021; 13(20): 4155. October, 2021. e-ISSN: 2072-4292 © 2021 Remote Sensing mdpi. Impact factor: 4.848. Citescore: 6.6 Scopus.

4. Marino S, Ahmad U, Ferreira MI, Alvino A. Evaluation of the effect of Irrigation on biometric growth, physiological response, and essential oil of *Mentha spicata* (L.). October 28, 2019. Special Issue 'Water – Evapotranspiration and Plant Irrigation Strategies'. Water mdpi, 2019; 11(11): 2264. ISSN: 2073-4441 © 2019 Special Issue: Water. Impact Factor 2.52.

5. Marino S, Ahmad U, Alvino A. VIs-image segmentation method for the estimation of agronomic traits in durum- and winter-wheat cultivars. July 19-22, 2021. 13th European conference on Precision Agriculture. Editor: John V. Stafford. ECPA, 2021; 403-409. July, 2021. eISBN: 978-90-8686-916-9 ISBN: 978-90-8686-363-1 © 2021 Precision agriculture '21 Wageningen Academic Publishers.

6. Alvino L, Marino S, Ahmad U, Alvino A. Investigating the global socio-economic benefits of satellite industry and remote sensing applications. 33rd IBIMA conference, Granada, Spain. April 10-11 2019. IBIMA. 2019; 33: 234-247. ISBN: 978-0-9998551© 2019 IBIMA. Web of Science, SCOPUS, and Clarivate analytics.

7. Ahmad U, Marino S, Alvino A. Sustainable Irrigation Management Strategies and relevant factors analysis. Scopus, Elsevier, 2022. June, 2022. ISSN 0378-3774, Cite score: 6.3 © 2022 Agricultural Water Management. Impact factor: 4.021. Submitting soon

8. Ahmad U, Marino S, Alvino A. Crop GIS mapping and free Computer application packages. Agric. Environ. Lett. 2022. e-ISSN: 2471-9625 © 2022 Agricultural & Environmental Letters. Impact factor: 2.529. Submitting soon

9. Ahmad U, Alvino A, Marino S. Precision Irrigation strategies for improving Tomato Water Use Efficiency: A review. Hort. mdpi, 2022. ISSN 2311-7524, Citescore: 3.4 © 2022 Horticulturae. Impact factor: 2.331. Submitting soon

10. Marino S, Brugiapaglia E, Miraglia N, Ahmad U, Di Brita A, Persichilli C. Exploitation of natural pastures by horses: Ecological aspects, production dynamics and biomass assessment using Snetinel 1 and Sentinel 2. Agriculture, Ecosystems & Environment, Elsevier. ISSN: 0167-8809. Impact Factor: 5.567. Submitting soon

11. Marino S, Ahmad U, Alvino, A. Assessment Wheat production and weeds infestation on spatial and temporal basis using remote sensing. Hort. mdpi, 2022. ISSN 2311-7524, Citescore: 3.4 © 2022 Horticulturae. Impact factor: 2.331. Submitting soon

Table of contents

List of Figures

List of Tables

List of Abbreviations and Acronyms

CWSI	Crop Water Stress Index
DSS	Decision Support System
ea	Actual Vapor Pressure
Ec	Electrical Conductivity (Soil)
Eo	Evaporation from U.S. Class A pan
es	Saturation Vapor Pressure
esa – ea	Vapor Pressure Deficit
es-ea	Saturation Vapor Pressure Deficit
ETa	Actual Evapotranspiration
ETc	Crop Evapotranspiration
ETm	Maximum Evapotranspiration
ETo	Reference Evapotranspiration
G	Soil Heat Flux Density
gs	Stomatal Conductance
H	Soil Heat Flux
IoT	Internet of Things
IP	Internet Protocol
IT	Information Technology
K_2O	Potassium Oxide
kc	Crop Coefficient
ky	Yield Response Factor
MQTT	Message Queue Telemetry Transport
N	Nitrogen
p	Depletion Coefficient

P_2O_5	Phosphorus Oxide
QoS	Quality of Service
Ra	Extraterrestrial Radiation
RDBMS	Relational Database Management System
RH	Relative Humidity
Rn	Net Radiation
Rnsw	Net Shortwave Radiation
RS	Remote Sensing
SQL	Structured Query Language
SF	Solar Fertigation
T	Mean Air Temperature
Tave	Average Temperature
TCP	Transmission Control Protocol
Tmax	Maximum Temperature
Tmin	Minimum Temperature
Tr	Transpiration Rate
TSS	Total Soluble Solid
u2	Wind Speed
UV Radiation	Ultra Violet Radiation
WiFi	Wireless Fidelity
WSN	Wireless Sensor Network
WUE	Water Use Efficiency
Zr	Root Depth
α	albedo
γ	psychrometric Constant
Δ	Slope Vapor Pressure Curve

λE	Latent Heat Flux
σ	Stefan-Boltzmann Constant

Development of a Solar Fertigation System for crop management using Environmental Forecast Analysis

Abstract

Agriculture technology is developed at a fast speed towards a new era. It has passed the evolution of Agriculture 2.0, 3.0 and is undergoing the agriculture 4.0 with advanced technologies for crop, soil and environmental optimization. Agriculture 4.0 connected with the help of the internet of things (IoT) can manage not only fertigation but also other agronomic techniques. The solar fertigation system is a smart fertigation system that integrates both, software and hardware to support the decisions of the farmer and capable of translating decisions into actions (e.g., fertilization and irrigation management) in an automated mode. The solar fertigation system shifts the manual fertigation into an era of automation and artificial intelligence. It collects the environmental data from the field, integrates them with the weather forecasts taken from the network and implements the correct fertigation solution for the type of the selected crop and the specific growth stage. These intelligent decisions of the solar fertigation system are supported by the decision support system (DSS) which provides autonomous decisions in all environment conditions. The DSS developed the agricultural processes from manual to automatic functions by maximizing productivity and precision. Though, the system recorded a few issues in challenging situations, on the basis of which, the study is meant to develop the system by addressing those issues. This study presents three objectives: 1) development of solar fertigation system database; 2) crop water management using web–based desktop platform; and 3) reference evapotranspiration assessment for all crops.
The development of the solar fertigation system was performed by using the latest systems and modern applications with some new functions such as a comparison of the two years' real-time collected data with the system's data. The solar fertigation system is negatively affected by natural hazards, animals, and overall, by wrong uses. After the system's development, differences in the data acquisition were the main concern. In an agricultural system, different processes perform the same work for getting results, while different equipment measure and generate different types of datasets. Data are analyzed by using a single platform to make it parallel as a single gauge. The study suggests various contributions that include:

1. Development of the solar fertigation system using the DSS which is based on microservice functions and allows agronomists to successfully deliver result-oriented datasets by analyzing the crop, and environmental datasets.
2. Analysis of the RDBMS database (Politecnico di Bari (PoliBa)) followed by the online application known as Solar Fertigation was generated. The online application transfers particular terminology to the differences in the data where a particular process activates the fertigation for crops in the field.
3. Weather forecast and meteorological data were acquired to estimate the best possible model for optimum crop growth and production. The temperature, humidity, UV radiation, air pressure, wind speed, and rainfall effects were compared with the crop growth stages from the periods 2019-2021 at four different regions in Italy with a mean annual rainfall of 806 mm (Campobasso), and 675 mm (Apulia region). High rainfall events affected crop production while average rainfall events tend to have a high demand for irrigation water requirement.

The studies found that present vegetation thickness is found within the ideal range though a more-better trend for grain production could have been formed. The system developed a particular long-term strategy, and crop management techniques for short- and long-time economic benefits in particular environmental conditions for higher yields and production.

Sviluppo di Sistema di un sistema di fertirrigazione solare per la gestione delle colture utilizzando l'analisi delle Previsioni Ambientali

Riassunto

La tecnologia agricola è sviluppata a una velocità elevata verso una nuova era. Ha superato l'evoluzione dell'Agricoltura 2.0, 3.0 e sta subendo l'Agricoltura 4.0 con tecnologie avanzate per l'ottimizzazione delle colture, del suolo e dell'ambiente. L'agricoltura 4.0 connessa con l'ausilio dell'internet delle cose (IoT) può gestire non solo la fertirrigazione ma anche altre tecniche agronomiche. Il sistema di fertirrigazione solare è un sistema di fertirrigazione intelligente che integra software e hardware a supporto delle decisioni dell'agricoltore e in grado di tradurre le decisioni in azioni (es. fertilizzazione e gestione dell'irrigazione) in modalità automatizzata. Il sistema di fertirrigazione solare sposta la fertirrigazione manuale in un'era di automazione e intelligenza artificiale. Raccoglie i dati ambientali dal campo, li integra con le previsioni meteorologiche prelevate dalla rete e implementa la corretta soluzione di fertirrigazione per il tipo di coltura selezionata e la specifica fase di crescita. Queste decisioni intelligenti del sistema di fertirrigazione solare sono supportate dal sistema di supporto alle decisioni (DSS) che fornisce decisioni autonome in tutte le condizioni ambientali. Il DSS ha sviluppato i processi agricoli dalle funzioni manuali a quelle automatiche massimizzando produttività e precisione. Tuttavia, il sistema ha registrato alcuni problemi in situazioni difficili, sulla base dei quali lo studio intende sviluppare il sistema affrontando tali problemi. Lo studio ha tre obiettivi: 1) sviluppo del database del sistema di fertirrigazione solare; 2) gestione dell'acqua delle colture tramite piattaforma desktop basata sul web; e 3) valutazione dell'evapotraspirazione di riferimento per tutte le colture.

Lo sviluppo del sistema di fertirrigazione solare è stato eseguito utilizzando i più recenti sistemi e applicazioni moderne con alcune nuove funzioni come il confronto dei dati raccolti in tempo reale dei due anni con i dati del sistema. Il sistema di fertirrigazione solare risente negativamente dei rischi naturali, animali e, in generale, di usi errati. Dopo lo sviluppo del sistema, le differenze nell'acquisizione dei dati sono state la preoccupazione principale. In un sistema agricolo, diversi processi eseguono lo stesso lavoro per ottenere risultati, mentre diverse apparecchiature misurano e generano diversi tipi di set di dati. I dati vengono analizzati utilizzando un'unica piattaforma per renderli paralleli come un unico indicatore. Lo studio suggerisce vari contributi che includono:

1. Sviluppo del sistema di fertirrigazione solare utilizzando il DSS che si basa su funzioni di microservizi e consente agli agronomi di fornire con successo set di dati orientati ai risultati analizzando la coltura e set di dati ambientali.
2. E' stata generata l'analisi del database RDBMS (Politecnico di Bari (PoliBa)) seguita dall'applicazione online denominata Solar Fertigation. L'applicazione online trasferisce una terminologia particolare alle differenze nei dati dove un particolare processo attiva la fertirrigazione per le colture in campo.
3. Sono state acquisite previsioni meteorologiche e dati meteorologici per stimare il miglior modello possibile per una crescita e una produzione ottimali delle colture. Gli effetti di temperatura, umidità, radiazioni UV, pressione atmosferica, velocità del vento e precipitazioni sono stati confrontati con le fasi di crescita delle colture nei periodi 2019-2021 in quattro diverse regioni italiane con una piovosità media annua di 806 mm (Campobasso) e

675 mm (Regione Puglia). Gli eventi di precipitazioni elevate hanno influenzato la produzione delle colture, mentre gli eventi piovosi medi tendono ad avere un'elevata domanda di fabbisogno di acqua per l'irrigazione.

Gli studi hanno rilevato che l'attuale spessore della vegetazione si trova all'interno dell'intervallo ideale, sebbene si sarebbe potuta formare una tendenza migliore per la produzione di grano. Il sistema ha sviluppato una particolare strategia a lungo termine e tecniche di gestione delle colture per vantaggi economici a breve e lungo termine in particolari condizioni ambientali per rese e produzione più elevate.

Thesis preface, scope and research activities

The need for agricultural production is growing due to climate change and other factors. It must be practiced with more affordable, safer and secure method. This makes it more important to evaluate the risks that need to be addressed so that all regions will benefit from innovative changes. The fourth agricultural transformation, which is further developing, includes a set of issues and solutions from the socio-economic, technological, and management perspective that requires to be addressed. However, the literature related to the agriculture 4.0 is limited in respect of its technological perspective. It delivers a plethora of systems without delivering metrics that present how these systems impact the agricultural system. A clear description of what systems are included in the development of agriculture 4.0 needs to be presented. In this regard, this thesis is aimed at contributing to the development of Agriculture 4.0. This thesis expands the research on the particular features of the solar fertigation system and crop management; contributing to show a novel path to agronomists and researchers, in particular in the adoption of solar fertigation, particularly suited for areas not served by electricity.

The present thesis is developed within the National Operative Program (PON) Italy of the European Commission to support the innovative industrial doctorate. The program supported University of Molise (UNIMOL), Politecnico di Bari (PoliBa) and Superior Institute of Agronomy (ISA) Lisbon, and a business partner Asepa Energy s.r.l. (Taranto) in agronomic research and innovation, invested in education, and research training for skills training infrastructure, technical assistance and development of the solar fertigation system. This thesis shows the best methods for plant water requirement and irrigation management by practicing the flexibility in managing the irrigation frequency, rate, and duration of irrigation supplies to successfully deliver appropriate water and fertilizer inputs to all crops.

The study has three objectives:

1. Development of solar fertigation system database using nine crops: The crop database is a compilation of data on the growth, irrigation, and development analysis collected from Food and Agricultural Organization (FAO) of the United Nations Land and Water. The analyses of the data were performed using validated methods with reference citations. The database contains nine crops that may be browsed and accessed based upon user-required information. The database supports existing crop growth, irrigation, and development and is of interest to agronomists and other researchers. The crop data collected, such as days to complete a crop stage, root depth (m), crop coefficient (kc), and crop yield factor (ky), depletion factor (p).
2. Crop water management using web–based desktop platform: This thesis proposes a reliable computer–based application able to analyses the crop and irrigation needs according to the particular environmental climate. The crop data is installed into the application which shows the particular irrigation frequency, interval and intensity at the particular time and day of the month. Upon reaching to that particular time, the system automatically and intelligently provides the irrigation and fertigation to the particular zone of the field which is required. This makes the crop growth highly efficient and more convenient to the users.
3. Reference evapotranspiration assessment for all crops: Reference evapotranspiration (ETo) is an important aspect of irrigation water management due to a basic input for assessing the crop water requirements. Different models have been developed for ETo assessment but several requires the daily meteorological data delivered by weather stations. This thesis assessed the two temperature–based models, such as Hargreaves–Samani (H–S) (Hargreaves and Samani 1985), and Blaney–Criddle (B–C) (Blaney and Criddle 1950). These models are considered as the most suitable and flexible models for the estimation of the ETo in all the environmental conditions. The data were collected from seven weather stations, such as Molise region (Campobasso East, Campobasso North, Campobasso West and Campobasso South), and Apulia region (Montemesola, Castellaneta and Marina di Ginosa).

This thesis is further arranged in the following chapters which are as follows:

Chapter 1 presents the introduction and background of the study Environmental parameters, their effects on crops development, soil and relevant parameters and their effect on crop development, reference evapotranspiration, crop evapotranspiration and the crops database.

Chapter 2 presents the DSS design and domain for the assessment of crops and environmental parameters. The chapter provides an overview of the system functions and how devices work, in an independent and dependent way. It further describes various system architects and their usage methods using the internet of things (IoT) approach. Major milestone of this chapter is to highlight service stacks for the DSS which operate and develop the functions of solar fertigation system. The services stack integrated with the DSS determine various precision agricultural related functions and buildup a sophisticated solar fertigation system.

Chapter 3 presents the results on the development of an agronomic solar fertigation system using the DSS, environmental and crop database. This chapter initially presents the functions of the solar fertigation system using the agronomic and crop data. Secondly, it introduces the analyzed work that are collected and analyzed in a variety of climatic conditions. The chapter also describes how the solar fertigation system supports the development of the database for the collection and analysis of the crop and environmental data. It further presents the weather forecast data and compare the collected data of the official forecast resources and solar fertigation system. The chapter discusses vital information related to the crop irrigation needs illustrated in the web–based desktop platform known as Solar Fertigation. It also shows a new irrigation approach which is considered as an intelligent system that irrigate the crops on day-to-day basis. The objective of this chapter is to test the intelligent solar fertigation system, and web–based Solar Fertigation desktop platform.

Chapter 4 presents the conclusion of the study and shows how an intelligent solar fertigation system is developed for crop optimization and weather forecast data. It delivers conducted research trends, challenges and problems experienced during this research study, and shows development of the system, domain and data collection method with a significant future trend.

Chapter 5, the final chapter, present the references that supports this study.

Chapter 1

Introduction

Water plays a significant role in maintaining agriculture, with food security and production responsible for above 90% of the total consumption (Porter et al. 2021; D'Odorico et al. 2018). It is more necessary than ever to understand the links between water scarcity, food production, food security, and environmental sustainability, especially in a changing world and in the context of global warming (Alvino et al. 2021). Accurate analysis of water resources – both in the context of magnitude and time is important to understand the water sustainability in agriculture. An accurate understanding of agricultural water needs could be utilized to classify those regions where water needs and its differences could potentially damage the reliability of food security and production, and for framing solutions to encourage sustainable water management. Studies report that better encouragement of sustainable water management leads to high food security and production (Porter et al. 2021; Sharma et al. 2019). Some studies have showed estimates of annual trends in water needs from crop fields (Chiarelli et al. 2020) while others developed sustainable systems that consider multiple crop management for high water use efficiency (Porter et al. 2021; Ara et al. 2021). The latter crop-system developmental studies have been typically emerged after the year 2008, delivering a significant snapshot of the system developmental phases, crop water needs and water use efficiency. For this reason, the aim of this thesis is to develop the decision support system by testing it in different regions and climatological conditions, and comparing its data with other. The data collected is available in a public domain for public use, comparisons, and analysis of their tests.

Chapter 1 is further structured in Section 1.1 global water demands. Section 1.2 Environmental parameters such as solar radiation, wind, humidity, temperature, and rainfall. While, Section 1.3 presents the crop parameters such as crop water needs, crop water availability, crop nutrient requirements, evapotranspiration, Hargreaves–Samani (H–S) model, Blaney–Criddle (B–C) model, and Penman–Monteith (P–M) model.

1.1. Global water demands

Agriculture is the major consumer of water in the world (Wallace et al. 2000). This is validated in river basins where agriculture experience minimum competition for water from residential or industrial sectors due to a smaller population and a lesser degree of industrialization. Such as, European irrigation is mostly focused on the Mediterranean, while in few countries about 85 % of the total freshwater goes for agricultural purposes (EEA 2009). So far, regular monitoring of water needs and utilization for agriculture is not available for Europe, partially due to unrecorded water consumption and regional differences in reporting and accounting. Modelling methods can be implemented to estimate net irrigation needs (aus der Beek et al. 2010). A study shows that the water demands in the United States from the years 1985 to 2010 increased (on average) and the future period from 2046 to 2070 will further increase (Brown et al. 2019). However, in China, the nationwide agriculture utilized 62.4% of water in 2016 (Ministry of Water Resources of China 2017). Canadian agricultural water demands are about 2.95 billion cubic meters for irrigation purposes in 2018. Agricultural irrigation in Alberta increased by 27% from 2016 to 1.9 billion cubic meters in

2018, accounting for more than half of the irrigation supplied to the agricultural sector nationally (Statistics Canada 2018). The water used during the crop growing season, which depends on the crop type, variety and the time of the growing season is known as crop water needs. Water needs can be mapped using meteorological analysis and data on crop management, and the variation between crop water needs and rainfall provides the crop water deficit (Myint et al. 2021). A study tested seven global hydrological systems supported by climate data reported differences in irrigation water demand among regions in the 21^{st} century. Those differences in irrigation water demand simulated variations reported small values across Europe (Wada et al. 2013). The studies further report that these changes in the irrigation water demand are getting to be increased due to environmental parameters that needs to be monitored and addressed within the certain limit of time. For this, the study evaluates major characteristics of the environmental parameters in the following section.

1.2. Environmental parameters

Crop growth, crop development, and crop yield are connected to environmental factors such as climatic condition, soil fertility, topography, and irrigation water quality. Supposing no constraints appear from soil condition and farmer and all environmental factors are at optimally available, users have to expect the maximum yield from the trials. When one or more factors are not available, it is considered a yield gap and a yield reduction appears in the obtained production. Agronomists reduce the possibility of these constraints (such as environment, and soil) by performing the zero pollution (in air, soil and groundwater) methods to secure the yield in all seasons of the year. It is of vital importance to understand the very well the environmental factors affecting crop growth and yield.

1.2.1. Solar radiation

Solar radiation affects crop growth in three major features: quantity, quality, and duration (Xin et al. 2019). The quantity of energy required to vaporize the available water at soil surface is known as the solar radiation. The quantity of radiation that strikes the evaporating surface is known by its position and month of the year. The greater amount of solar radiation is available in summer, and the lower in winter. For a certain limit, the higher the sunlight a crop receives, the greater its potential for development by photosynthesis conductance. Due to variations in the location of the sun, the potential solar radiation variates at different latitudes and in changing seasons. The actual radiation striking the evaporative surface is dependent on the turbidity of the environment and the clouds presence that reflect and take in high amount of the radiation. When estimating the impact of solar energy on evapotranspiration, it is to note that some of the energy is used to vaporize the water body. Some of the radiation is used to warm up the environment and the soil surfaces (Allen et al. 1998). Quality of the light refers to the wavelength of light. Crop plants absorb the red and blue lights and have greater effect on crop growth. Both of these lights are responsible for flowering and leaf vegetation, respectively. However, duration (or photoperiod) is the quantity of time a crop plant experiences the light. Photoperiod maintain flowering in crops. Researchers considered the plants, that are mostly dependent on photoperiod, as long-day or short-day (Ma et al. 2021).

Jones (2013) reported that the radiation effects the crop in four main ways such as:

a. Thermal effects: Radiation is an important method of energy transfer between plants and the environment. It provides the required energy to the plants, while a high amount of this energy converts to heat and motivating other important processes such as transpiration, tissue temperatures, metabolic processes and the balance between them.

b. Photosynthesis: A particular amount of the solar radiation absorbed by plants is used to create compounds that drive energy-requiring biochemical reactions. These compounds are composed of inorganic phosphate and ADP. This support of the energy in solar radiation for the photosynthesis process is an important feature of plants and delivers the major input of free energy into the environment.

c. Photo morphogenesis: The quantity, direction, period and spectral distribution of shortwave solar radiation provides an important role in regulating the plant growth and development.

d. Mutagenesis: Extremely shortwave, very energetic radiation, with the ultraviolet, X- and γ-radiation have damaging effects on plant cells, specially impacting their genetic structure which leads to mutation.

1.2.2. Air temperature

The solar energy absorbed into the environment and the heat produced by the surface of the earth rise the air temperature. The sensible atmospheric heat transmits the energy to crops and is considered a controlling effect on the amount of evapotranspiration. In warm, sunny days the damage of water performed by evapotranspiration is higher than in cool and cloudy days.

Air temperature has to be analyzed in different ways which are as follows:

Direct effect

Air temperature directly affect the physiological responses of plants and crops. Global climate changes in temperature and rainfall patterns will continue to influence the ecology of agricultural system. Temperatures are predicted to rise with larger variations in higher latitudes (Climate Change 2013), while rainfall pattern changes are predicted to be rather minimum (Climate Change 2013). Some countries have already showed a rise in rainfall pattern, while others have reported decreased values with changes in the frequency and intensity (Vandandorj et al. 2017). Particularly, as temperature and rainfall are not predicted to change in parallel, discerning the ecological responses of climate effects will need understanding the effects of high temperature at multiple levels of soil moisture or rainfall.

Indirect effect

The above direct negative temperature effects on crops are further affected through the indirect temperature effects. For example, rising temperature will increase the crop water demands, that leads to the additional crop water stress from additional water pressure deficits, ultimately effecting the soil moisture and crop yield (Zhao et al. 2016). However, a developed phenology from rising temperatures leads to a decreased growing period and less period of crop water use within a growing season. These indirect temperature effects are considered as an important factor, but are not optimally quantified. Other indirect temperature effects are regular heat waves and potential temperature impact on weeds, pests, and crop diseases (Lesk et al. 2016). Improvements in management intensity and yield growth could automatically develop yield sensitivity to the environment (Lobell et al. 2014).

Though climate impact analysis is not convincing to adequately address the effects of changes in extreme conditions on crops (Müller et al. 2010), especially the bad effect of high temperature, categorized as a major threat to crop production in all regions of the world. Studies modelling the effect of heat stress on crop yield have been limited to particular regions (Hawkins et al. 2013) or do not determine impacts on crop yield (Gourdji et al. 2013). Moreover, latest studies present only a partial analysis of uncertainty related to different climate change projections (Nelson et al. 2010). Finally, predicted advantages from CO_2 emission effects are a large resource of insecurity (Deryng et al. 2014).

Temperature effects crop processes, such as transpiration, respiration, photosynthesis, development, and flowering. Plants behave like poikilothermic organisms which means that they adapt to the temperature of the environment in a gradual means. The impact of chemical reactions is provided by the temperature as reported by Vant Hoff's law which states that the temperature from 10 to 30 °C, the reaction rate doubles as the temperature rises from 10 °C (Perniola 2021) (as shown in Figure 1.1).

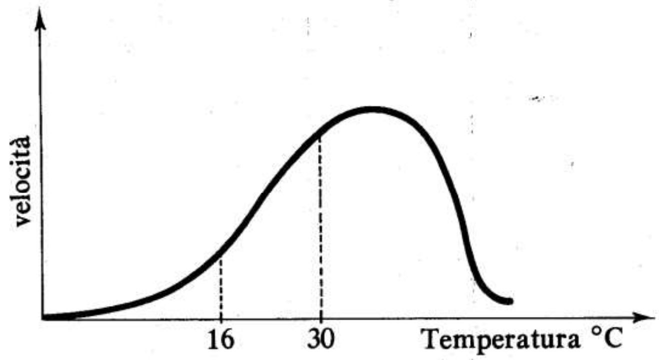

Figure 1.1. The non-linear relationship between the temperature and plant growth velocity measured on maize as a function of temperature (Lehenbauer) (Perniola 2021).

During the temperature increase, photosynthesis, respiration and transpiration increase. With the combination of the day-length, temperature also influences the change from vegetation to reproduction. Depending on the crop type and environment, the influence of temperature can either negatively or positively affect the crop plants (Htoo et al. 2021). In general, crops such as spinach, radish, and lettuce grow optimally from 13° to 18° C, while crops such as tomato, petunia, and lobelia show optimal growth from 18° to 23° C. Low temperatures minimize energy utilization and maximize sugar storage. Thus, affecting the crop, such as winter squash, to maximize their sugar content. However, stressed temperatures provide the stunted growth and low-quality vegetables. Such as, high temperatures provide bitter lettuce plants (Zabel et al. 2021).

Crops growing in cold environmental conditions need a specific number of days with low temperature. Taking note of the days of low temperature is important for its growth and development. Crop like Peach requires 700-1,000 hours from 0 to 7 °C into their dormant period and prior to their growth initiation. Lily plants require 45 days of about 0.5 °C before the blooming period (Horsáková et al. 2016).

1.2.3. Relative humidity

The ratio of water vapor available in the air to the quantity of water the air could hold at the present pressure and temperature is known as the relative humidity (RH). Hot air can hold a higher amount of water vapor than cold air. The empirical method of determining the RH (Alexandris et al. 2003) is as follows:

$$RH\ (\%) = \frac{\text{Water in air}}{\text{Water air could hold}} \qquad 1.1$$

The values of RH are determined in percent. Water vapor transfers from high relative humidity to low relative humidity levels. The higher the difference in humidity, the faster water transfers. This parameter is significant because the amount of water transfer directly influences the plant's transpiration level. The relative humidity is available close to leaf cells and contributes in its growth. During the stomatal opening, water vapor of the leaf rushes out into the nearby atmosphere, and a higher amount of humidity creates around the leaf stoma. By saturating this particular air zone, it minimizes the difference in relative humidity between the air gaps of the stoma and the air close to the leaf area (Liu et al. 2021). Ultimately, it influences the rate of transpiration. When the fast air blows, the humidity decreases and the rate of transpiration increases. Therefore, the rate of transpiration is higher in hot and windy environments. Alternatively, the rate of transpiration is slow in cool and non-windy environmental conditions. Dry and hot conditions usually occur during the summer, which influence the plants and wilt quickly. With an interrupted supply of water to the roots and the leaves, turgor pressure decreases and leaves start to wilt.

1.2.4. Wind speed

The progression of vapor extraction from the leaf surface is highly dependent on wind and air turbulence which transmit big amount of air at the evaporating leaf. During the vaporization process, the air above the leaf surface start to saturates with water vapor. In case the air is not regularly exchanged with drier air, the force for water vapor extraction and the rate of evapotranspiration decreases.

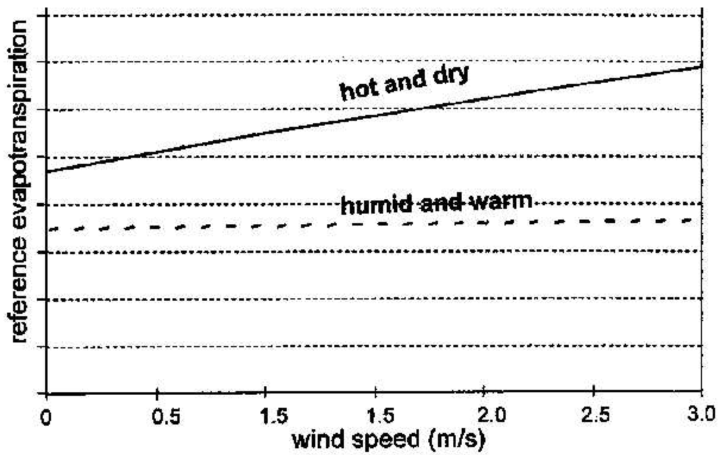

Figure 1.2. Impact of wind-speed on evapotranspiration in humid-warm and hot-dry environmental climates (Allen et al. 1998).

The mutual effect of climatic factors for two different climatic conditions influencing evapotranspiration as shown in Figure 1.2. The evapotranspiration requirement is high in hot-dry environment due to the dryness of the air and the quantity of energy available as radiation. In this situation, a high amount of water vapor is stored in the air and the wind forces the water to shift allowing a specific amount of water vapor to be taken up. However, in humid environments, the air humidity and the clouds cause the evapotranspiration to be lower. The influence on evapotranspiration of maximizing wind speeds for the two environments is shown (Figure 1.2). The drier the environment, the higher the effect on ET and the higher the curve slope. For humid environments, the wind just replaces saturated air with less-saturated air which exclude the heat energy. Ultimately, the wind speed influences the rate of evapotranspiration with a lesser extent than under arid environments where minor differences in wind speed result in greater differences in the rate of evapotranspiration.

1.2.5. Rainfall

Precipitation water is the significant resource of water supply to the crops If combined with irrigation, this could provide significant good results depending on the condition and considering the fact that availability of water more than the required can harm. In new irrigation projects, for instance to assess the probable amount of rain (e.g., 3 years out of 5 years) that might fall in the study area, in order to calculate the volume of a large water resource such as dam, canal, river or water extraction bodies. It is important to define a drainage network on the basis of the probable rainfall.

Rainfall is not always useful at the time, quantity in which it is acquired. A particular quantity of rainfall may be unavoidably wasted whereas some may even be damaging. Likewise, to the total rainfall differences, so does the effect of the rainfall. The primary resource of water for agricultural production for most of the world is rainfall. Three main characteristics of rainfall are its amount, frequency and intensity, the values of which vary from place to place, day to day, month to month and also year to year. Precise knowledge of these three main characteristics is essential for planning its full utilization. Information of the amount, intensity and distribution of monthly or annual rainfall for the most important places in the world is generally available. Long-term records of daily rainfall have been compiled for years; norms and standard deviations have been worked out; floods and droughts have been defined and climatic zones of potential evapotranspiration less precipitation have been mapped from rainfall patterns and crop studies. Investigations using electronic computers are continuously in progress and efforts are being made to predict future trends in order to refine planning.

Rainfall distribution over the year is also an important and convincing factor for crop growth. Uneven distribution minimizes the extent of crop growth while an even spread maximizes it. A good distribution of rainfall in normal showers is highly conducive to crop growth than heavy showers. Such as, yearly rainfall is lesser than 100 mm in the desert countries of the Middle East, so it may be effective for crop growth. In Pakistan and India, the frequency, intensity, and amount are high from June to August and thus the effect on crop growth is low. However, from November to April, most of the rainfall is considered to have a good effect on crop growth and production.

If the crops need water, both the irrigation and rainfall should be provided to the crops so that the crop water requirement satisfies the needs of the crops in a given situation. If anyone has to be added with the second, this is known as secondment irrigation which completes the needs of the crops to grow. When rainfall initiates, the water droplets are absorbed by the soil in various shapes which also decides the structure of the soil, and in this way part of the rainfall water droplets (ranging from 1-4.5 mm in size) can be used by the root zone of the crops and others escapes in different shapes such as leaching, drainage, and (Brouwer et al. 1986). With a highly efficient water management strategy, surface run-off could be managed successfully. Only additional water is removed by surface drainage, deep percolation or by sub-surface drainage (Figure 1.3). For a particular field, run-off is assessed by computing the formulae established for different environments, as shown in USDA Field Manual for Research in Agricultural Hydrology (Brakensiek et al. 1979).

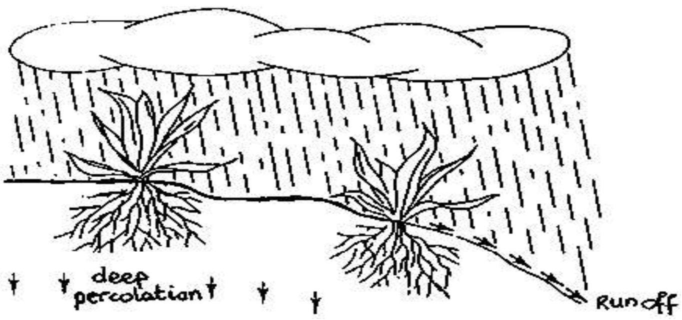

Figure 1.3. It shows that the deep percolation takes part in escaping the water content received from the rainfall, whereas the runoff is high in amount. In windy/stormy season, the runoff and deep percolation reveals different values depending on the region and rainfall amount received at the soil surface (Brouwer and Heibloem 1986).

The water that is disposed-off in the shape of deep percolation or run-off stores in some other resource of the nature and could be utilized in any other usage or part of it is absorbed by the soil which remains stored for longer time and in a fresh form. The plant's root zone can easily utilize and uptake the water for its growth, nourishment and further development. Part of the water content that is utilized by the crops and soil is effective rainfall, which is different in every region of the world depending on its climate, rainfall yearly durations, soil structure and texture, root-zone depth, and variety of planting factors.

In many regions of the world, especially in developing and least developing regions, there is a lack of a system due to which heavy rainfall creates huge devastation and affects plants in the shape of high runoff and drainage or floods. In the special case scenario and especially in mountainous regions, the soil passed with the floods (or heavy rainfall) is not able to absorb any further water content, part of it drains off (or run-off) over the soil surface but part of it goes deep into the soil where deep percolation initiates and the plants root-zone are better to uptake it. This process could affect the water table into the soil to rise up which is easily available for the plants and other nature (Brouwer et al. 1986).

1.2.5.1. Factors affecting effective rainfall

Effective rainfall depends on different factors in which the primary factors include the climate and its linked variables, crops development stage and characteristics, and soil texture and structure may affect either alone (lower effects) or all in a collective form (higher effects) impacting the value of effective rainfall (Dastane 1978).

Table 1.1. Different components which impact the effective rainfall in a high and low volume with their dependent features (Allen et al. 1998).

Affecting factor(s)	Dependent feature(s)
Crop	Crop development stage, crop rotation, degree of ground cover, and crops root-zone depth
Land	Level of land-slope, and topography
Water	Temperature, suspended materials, clay turbidity, viscosity level, and dissolved salts such as Na^+, NO_3^-
Soil	Texture, structure, level of organic matter, salt quantity, and bulk density
Management approaches to maintain soil quality	Tillage, soil conditioners, levelling degree, and field layout such as bunding, terracing, ridging

Crop and effective rainfall

Effective rainfall is directly proportional to the amount of water uptake by the crop. Crop parameters effect the rate of water uptake are the degree of crop cover, rooting depth and crop stage. Evapotranspiration is usually high in vegetative and the flowering period and thus may deteriorate the maturity. Soil moisture preserved in deep layers are used when roots penetrate into them. Deep-rooted crops are considered to increase the proportion of effective rainfall in a particular area; thus, the nature of the crop is a vital factor in determining the effective rainfall. Rainfall just prior to harvest is considered highly ineffective for most crops. Rainfall which degrades the yield production must be managed as its ineffective. The crop is a vital factor in interpreting the basic information for effective rainfall. Therefore, the seasonal requirements of major crops in a particular area are taken into consideration when the extent of effective rainfall is evaluated (Dastane 1978).

Land structure and texture

The land composed of slopes and hills are not considered to absorb a higher rate of rainfall so that it could reach to the ground water-table or up taken by the root-zone where there is a higher opportunity for run-off, but has a higher chance to absorb a maximum amount of water-content received from rainfall at the levelled and successive land where there is a maximum chance for deep-percolation, and seepage. The hills, mountains, flat land/slopes, play-grounds, roads, agriculture or buildings have some major contributions in affecting the effective rainfall.

Water-table levels

Water shifts upwards in the soil layers is known as capillary rise, thus minimizing the moisture deficit and the rate of effective rainfall. The levels of water tables variate at each season. Prior to the rainfall, the water table may be deep; during the rainy season and that can rise to the soil surface. Capillary rise supports these horizontal flows in the sub-soil. Due to these variations, the division of soil water to the crop needs is variable and the rate of effective rainfall differentiates (Dastane 1978). After the rainfall, the rainwater changes its characteristics in many other forms, especially after striking at the earth. These special characteristics further mix with the different types of salts present in soil including the sodium or nitrates, viscosity, temperature, turbidity, or whether they are offered directly or indirectly at the soil surface. All of these physical, chemical characteristics and other attributes of rainwater content and soil governs the level of effective rainfall in the particular soil (Alvino et al. 2021).

A study conducted to collect data on the effect of a water-table in maize crop grown in irrigated and rain fed conditions. The data illustrated that crop production decreased as the depth of the water-table increased while this change being faster in rain fed than in irrigated conditions. Grain moisture substance and seed weight showed a linear response to the water-table depth. The height of the plants and leaf senescence showed low values as water-table depth increased (Alvino et al. 1986).

Soil factors

Fraction of the rainfall is affected by the soil moisture retention level whereas infiltration rate of the rainfall is affected by the soil properties of the given region. The water holding capacity plays a crucial role for increasing or decreasing the level of effective rainfall and it also equates the fraction for the effective rainfall at any given circumstance after the rainfall. Water holding capacity of the soil depends on the soil structure, organic matter content, texture, depth. The water holding capacity is directly proportional to the soil texture. The water content present in different soils at different regions is completely different due to the reason that if the soil has more depth, it will have much more concentration of effective rainfall, which ranges from 10 mm meter-1 (sandy soils) to 100 mm meter-1 (for clayey soils). Other factors depending on the effective rainfall are the infiltration rates and hydraulic conductivity; if these are higher, there will be a high amount of effective rainfall with low runoff levels. Soil moisture content also affects the effective rainfall in the way that if its higher, the infiltration rate will be minimum as well as the surface runoff will be higher which will decline the level of the effective rainfall.

After the irrigation, if the rainfall occurs, the water is lost in the form of surface run-off and could not be used by the soil, plants and could be stored, as the initial stage of the soil moisture level regulates the effective rainfall amount in a significant manner. In the regions where there is a high quantity of rainfall with irrigation water availability has shown the low level of effective rainfall where those regions where there is integration among the both, has been noted to be having a higher concentration of effective rainfall.

1.2.6. Soil parameters

The soil evaporation procedure strictly depends on the hydraulic connectivity of the soil saturated zone and the surface (Maxwell et al. 2016). Gardner et al. (1958) analyzed the stable evaporation from a water surface in laboratory conditions, estimating the rising liquid movement which is based on the Buckingham-Darcy hypothesis. The study further presents soil types and then soil water potential in the below sections.

Soil is a natural structure consists of solids (organic matter and minerals), liquid, and gas that develop on the surface of earth, requires space, and is categorized by either one or both, layers or horizons, that are different from the initial product by the losses, transfers, additions, and alterations of matter and energy, or the capacity to be an important resource for plants in a natural atmosphere (Soil Survey Staff 1999). The soil composition is distinguished into 6 primary types. They are clay, sand, peat, chalk, silt, and loam. The wide adoption of clays is increased due to their significant features such as natural occurrence, less costs, and compatibility (Sabouri et al. 2020). Clay is made of silicate, alumina and other ion-balanced particles in its layers such as nano-layers. These Nano-layers are known as aluminum (Al), magnesium (Mg), zinc (Zn), iron (Fe), and calcium (Ca) (Murugesan et al. 2020). Sand is made of granular substance which consists of fine pieces of rock and mineral substances. Sand has different structures but is described by its particle size. Sand particles are lesser in size than gravel and rougher than silt substance. Peat is called as turf which is the preservation of partly decomposed organic or vegetation substance (Hugron et al. 2013). The peatland ecology ranges from 3.0 to 3.7 million square kilometer (McGrath 2020). Chalk is a white, porous, soft carbonate substance. It is composed of limestone of the inorganic calcite and initially formed under the ocean by the compression process of small plankton structures that settled at the sea floor. Loam is considered a soil which is composed of sand particles (with size greater than 63 micrometers), silt particles (with size greater than 2 micrometers), and a little quantity of clay particles (with size greater than 2 micrometers) (Kaufmann and Cutler 2008).

1.2.7. Soil water potential

Soil water potential is estimated as potential energy at per unit amount of water, comparative to the reference water potential. As soil water has different forces in the form of soil particles through which water is absorbed into the soil, potential energy varies from point-to-point, and thus the potential energy is different too (Horrocks and Vallentine 1999). This could be described in an empirical approach as below:

$$\text{Soil Water Potential} = \text{Force} \times \text{Distance} = mgl = pw\ Vg\ l\ (Nm) \qquad 1.2$$

Water flows from greater potential towards lower potential. This justifies the second law of thermodynamics, as energy drifts along the incline of the intensive parameter. Water transfers from a high energy zone to a low energy zone till the particular zone reach the equilibrium (Figure 1.4). For instance, in condition when soil water potential reaches to -50 kPa, water move to the additional negative 150 kPa (in total will be -100 kPa) to become highly stable (Campbell et al. 2021).

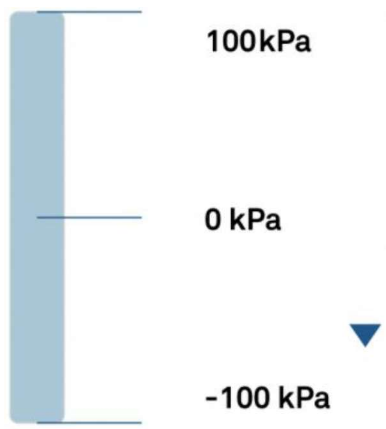

Figure 1.4. Presentation of the water movement from a higher tensed energy position to a lower tensed energy position (Campbell et al. 2021).

Water moves through soil and roots, through the xylem tissues of leaves evaporate the water moisture in the sub stomatal opening of the leaf. The driving force for this water movement is the gradient. So, the leaf water potential should be lower than the soil water potential for the water to flow. For example, when the soil is at -0.2 MPa and the roots are slightly more negative at -0.4 MPa. Sin this particular case, the roots will pull-up the water from the soil which will move up through the xylem and evaporate through the leave stomatal tissues. While the atmosphere, at -100 MPa, is a strong driving factor of this gradient (Campbell et al. 2021).

1.2.8. Total available water (TAW)

Total available water designates the ability of a soil to hold water against the gravitational forces. Water holding capacity refers to the amount of water held in the soil against gravity, or the total volume of water in the soil at field capacity. The amount of water that is available into a well-drained soil and which could contain a specific level of water against the gravitational forces is known as field capacity. If water is not provided, the root zone is dried and resultantly the crop water demand increases which impacts yield, productivity as well as root zone of the soil. Crop plants continuously require soil water for their growth and development but at a certain stage the time comes where the water is held tight to the soil particles (in some cases much far), making it very tough for the crop plants to utilize. At some point, the crop plants can no longer utilize the water due to any reason ultimately impacting the crop plants and the start of the wilting point initiates. The water content stage where crop plants wilt (permanently) is known as the wilting point (Allen et al. 1998).

The water level when maximizes the soil field capacity, it cannot be further stored into the soil and cannot hold against the gravitational forces which ultimately drains out, and water level when appears low than the wilting point it cannot be used by crop plants due to many factors, so the total available water (root zone) can be computed as the difference between the water level at the field capacity of the given soil and crop wilting point of that specific day (Allen et al. 1998):

$$T_{AW} = 1000\ (\theta_{FC} - \theta_{WP}) \times Z_r \qquad 1.3$$

whereas

TAW = Total available soil water in the root zone (mm)

θ_{FC} = Water content at field capacity ($m^3\ m^{-3}$)

θ_{WP} = Water content at wilting point ($m^3\ m^{-3}$)

Zr = Rooting depth (m).

1.2.9. Readily available water (RAW)

Readily available water (RAW) depends on two factors, such as Taw and the plant factor. The fact is the water is available in the soil until wilting point approaches which impact plants roots due to which the crop plants are not able to uptake the water for their growth and development. Though the soil full of moisture constitutes enough water to be uptake by the crop plants and further utilized by them where ETc is simply equal to the water uptake. In the condition, where the soil water content is limited into the given soil, the water molecules are strictly adhered to the soil layers which is difficult for the plants to be utilized. In some cases, the soil water content becomes extremely short and hits the threshold. In this specific scenario, the soil cannot transport the water content to its adjacent soil articles, also roots could not function to uptake the water content which ultimately maximizes the transpiration demand of the crop plants and later on the stress factors initiates which could seriously damage the crop plants development and growth. Somehow, the fraction of total available water (TAW) in soil which the crop plants can uptake besides the crop root-zone is known as readily available water in the condition if the crop plants do not experience any stress factor (Allen et al. 1998):

$$RAW = p \times TAW \qquad 1.4$$

whereas

RAW = Readily available soil water in the root zone (mm)

p = Average fraction of Total Available Soil Water (TAW) that can be depleted from the root zone before moisture stress (reduction in evapotranspiration) occurs (0 - 1)

Table 1.2 shows values for the no stress factor, p. The p-value is different in each crop which depends on the region to region, atmosphere and other conditions too, which starts from the shallow rooted plants with value (0.30) and reaches to the value (0.70) for deep root plants. The high rates of ETc are considered as (> 8 mm d^{-1}) while that of the low rates of ETc is considered as (< 3 mm d^{-1}) depends on the region and atmosphere. Though the p-value (0.50) is generally used for the crops which have missing crops data (Allen et al. 1998).

Table 1.2. Presentation of the rooting depth (Zr), and depletion factor (p-value) under no-stress condition for different crops. The table reports particular list of crops which were considered for trials. The FAO Manual 56 (Allen et al. 1998) reports the complete list of crops (Allen et al. 1998).

Crop(s)	**Root depth (m)**	**Depletion factor p-value**
Citrus (*Citrus sinensis* and *Citrus limon*)	0.8–1.1	0.50
Olive (*Olea europaea*)	1.2–1.7	0.65
Soybean (*Glycine max*)	0.6–0.7	0.50
Potato (*Solanum tuberosum*)	0.4–0.6	0.35
Cabbage (*Brassica oleracea var. capitata*)	0.4–0.5	0.35
Onion (*Allium cepa*)	0.3–0.6	0.30
Pepper (*Capsicum annuum*)	0.5–1.0	0.30
Tomato (*Lycopersicon esculentum*)	0.7–1.5	0.40
Watermelon (*Citrullus lanatus*)	0.8–1.5	0.40

The p-value is defined as “The function of the atmospheric evaporation strength impacting crop plants”. In the scenario with low ETc values, the given p-values are greater than the ETc high rates. In the scenario where there is a low ETc, the p-value should be higher as 20% more as given values (Allen et al. 1998).

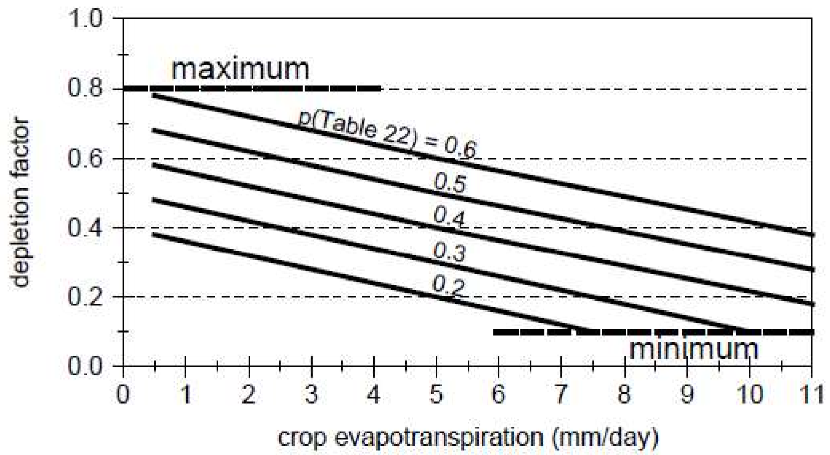

Figure 1.5. Depletion factors (p-values) at different evapotranspiration conditions (mm day^{-1}) (Allen et al. 1998).

Table 1.3. Determination of readily available water and total available water for a healthy onion, tomato and maize crop. The soil structure is assumed as the loamy sand, silt and silty-clay soils (Allen et al. 1998).

Crops	**Root depth (Zr)**		**p-factor**			
Onion	0.4		0.30			
Tomato	0.8		0.40			
Maize	1.2		0.55			
Loamy sand	**θ_{FC} (m^3 m^{-3})**		**θ_{WP} (m^3 m^{-3})**			
	0.15		0.06			
Silt	0.32		0.15			
Silt clay	0.35		0.23			
	Loamy Sand		**Silt**		**Silt Clay**	
	Taw	**Raw**	**Taw**	**Raw**	**Taw**	**Raw**
Onion	36	11	68	20	48	14
Tomato	72	29	136	54	96	38
Maize	108	59	204	112	144	79

To estimate the resistance of crops to water stress in the fraction (p) of Taw is not completely established. The values of root water collected is majorly affected by the energy scale of the soil potential in the form of the hydraulic conductivity. So, soil matric potential is one of the factors with different soil water contents to affect the value of p which is a function of the soil type.

1.3. Crop parameters

The study has parametrized the discussion on crop coefficient (kc), crop water stress coefficient (ks), crop water requirements, crop nutrient requirements, various crops assessment, reference evapotranspiration (ETo), and crop evapotranspiration (ETc). The detail of each of the parameter is given as below.

1.3.1. Crop water needs

Crops need water for evaporation and transpiration. The plant roots absorb moisture from the soil for their growth. The major portion of this water does not stay in the plant, but evaporates to the atmosphere in the form of vapor through the leaves and stem, and is known as transpiration. The high rate of transpiration occurs in the day time. Water from an exposed water resource evaporates in the form of vapor to the atmosphere during the day time. This also occurs to water on the leaves and stem of a plant and the soil surface, and is known as evaporation (Li et al. 2021). The crop water needs therefore are composed of evaporation and transpiration, that are combined in one word, evapotranspiration. The crop water need is generally estimated in mm day^{-1}, mm $month^{-1}$ or mm $season^{-1}$ in technical studies. For example, the crop water need of a particular crop in a hot and dry region is 2 mm day^{-1}. This means that every day the crop will be provided a water layer of 2 mm over the complete field on which the crop is cultivated. It is not considered that this 2 mm has to definitely be provided by irrigation or rain in the season. It is, for sure, yet likely to provide, for example, 5 mm of irrigation water each 7 days. The irrigation water provided will then be preserved by crops in the root zone and steadily be utilized by the crops: each day 2 mm (Keck et al. 2021). If the crops are not provided the optimum water needs, their coefficient is disturbed which is discussed in the following section.

1.3.2. Crop water requirements

The water content available in the soil are needed by crops to address water-loss occurred through ETc, and is known as crop water requirement of the given crops. This scenario must satisfy the condition including a uniform crop which actively grows, shades completely at the soil surface, disease free with soil conditions must be provided favorable (Doorenbos et al. 1996). The crops depend on several factors to reaches its complete developmental stage under the given climate, which are:

a. **Climate:** Crops transpire more water in hot and sunny seasons and there is a higher demand for soil water moisture at the root-zone of the crops.
b. **Crop type:** Crops water requirement also depends on different types such as rice, cotton, sugarcane, and wheat have high demand of water and moisture levels.
c. **Crop growth stage:** Crops have different water-content demands in different growth stages such as before the maturity, most crops have high water requirement demand.

Study performed by Augustin et al. (2015) on maize crops for the parameters such as crop water requirements, and crops yield at water stress by CROPWAT and GIS at optimal irrigation schedules in the summer season. It revealed the crop water requirements from 30.7 (mm) month^{-1} to the 200.8 (mm) month^{-1} from April till September in 2015. The ETo was recorded from 0.47 (mm) to 3.08 (mm), while the water-content requirement at the given season was 833.4 (mm). The field capacity at the given tested terrain was recorded 70% under the favorable weather conditions, whereas performing the fixed intervals at each stage experienced a significant yield reduction of 2.5% in the given crops.

Water requirements for each crop type, crop development stage, soil structure/texture, and weather conditions are different at each zone of the region and continuously changes as the weather and condition changes (Steduto et al. 2012). Other factors that affect the crop yield production are the experimentation trials and their setup according to the region, these parameters govern the quantity of irrigation turns and application stages, and net crop water requirements for the given crops at the tested field (India Agro Net 2018).

1.3.3. Crop nutrient requirements

Alongside with the water availability, the nutrients such as nitrogen, phosphorus, and potassium are also required by the crops for their better growth and significant yield production. These majorly required nutrients may be mixed with some plant residues, organic manures, and must be provided in the form of inorganic fertilizers. Local and regional guidelines also provide the crop nutrient requirement database for different crops assessed through the environmental (such as soil characteristics), crop factors (crop growth stage, and variety), and weather conditions and applied in the tests accordingly to adapt new paradigms, novel metrics should be brought forward and developed to better communicate changes in crop nutrient requirements. While there are few robust measurements for crop nutrient requirements (e.g., bulk density and pH), the way is needed to reliably estimate the crop biological processes. However, estimating crop nutrient requirements may be costly and complex to translate into management suggestions (Regents of the University of California, 2020).

The primary nutrients required by the crops are N, P, and K and are taken by the crops into the form of NO_3^- and NH^{4+}, $H_2PO_4^-$, HPO_{42}^- and PO_{43}^-, and K^+, respectively. Whereas the secondary nutrients including Ca, Mg, and S are consumed by the crops in the form of Ca^{2+}, Mg^{2+}, and SO_{42}^-. The other nutrients called Micronutrients also required by the crops such as B, Cl, Cu, Fe, Mn, Mo, Ni, and Zn in the form of BO_{33}^-, Cl^-, Cu^+, Cu^{2+}, Fe^{3+}, Mn^{2+}, MoO_{42}^-, Ni_2^+, and Zn_2^+.

1.3.3.1. Primary nutrients

Nitrogen (N)

The crops utilize Nitrogen in an abundant quantity, depending on the climate, crop and soil due to its value and more presence in the soil surface. If the crop experiences a lack of Nitrogen due to indirect availability of the N in soil surface as it happens in many regions of the world, the crops will show retarded poor plant growth, chlorotic leaves and becomes yellow or pale-green due to inability of making sufficient chlorophyll. In many soils, the availability of N could not be possible to crops as they are available in the form of bacteria, soil organic matter, and plant residues. In the case of soil microorganisms, they perform mineralization and utilize their food to ultimately convert the N so that it is further available to the crop's root-zone. Not available as a direct nutrient, but the soil particles get nourished in a long-term process and further aids the crops root-zone in the form of Mineral-N in NH^{4+} (ammonium) and NO_3^- (nitrate) forms.

Phosphorous (P)

The crops utilize Phosphorus from the soil organic matter and considered as one of the second-major nutrients and the lack of which causes declined fruit yield, leaves premature senescence, poor boll retention (cotton), dark green leaves, delayed flowering, stunted crop growth, and lower grain quantity. The crops utilize the phosphorus in the form of inorganic phosphates as P is abundantly available in the soil in different forms. The different soil microorganisms present into the soil convert the P into the form of inorganic phosphates to be available to crops for their better growth and production which is present in lower quantity, while when added through fertilizer, manure and compost directly immobilizes into the soil system. This inorganic phosphate available for the crops in soil is mixed up into the soil particles and then transformed towards the crops root-zone.

Potassium (K)

The crops need potassium in a good quantity for their better production in various forms such as in the form of soil solution and exchangeable potassium available in a very minute fraction in soil. K deficiency creates problems in crops such as chlorosis between leaf-veins, purple spots on leaf undersides, leaf tips curling, brown scorching, seed and fruit development, root development, plant growth. The K present in the form of soil solution as well as the exchangeable potassium are considered as unstable in the soil and is not tightly held within the soil while the mineral K is considered a stable form which is available in soil for a longer duration of time.

Secondary nutrients

The secondary nutrients such as calcium (Ca), magnesium (Mg), and sulfur (S) are used by the crops as equally as the primary nutrients in many different forms but in a very lower quantity. In many soils, the adequate amount of secondary nutrients is available in soil but are not strictly adhered to the soil particles. Lack of these secondary nutrients initially affect older leaves and cause deficient leaf growth, color loss in leaf veins, leaf tips progress inward, leaf tips sticking together, crop stunting, slow root development, reduced photosynthesis, roots develop dark color and ultimately crops die.

Micronutrients

Micronutrient deficiencies create serious crop production problems and highly affect their yields. Micronutrients such as boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), and zinc (Zn) are needed by the crops in such as lower fraction but are supposed to be a significant contribution in their growth, development and yielding capacity. The micronutrient such as B aid in metabolic regulation and it lack causes bud dieback, Cl develops the ionic balance within the crops leaves such as photosynthesis, Cu aids in Vitamin-A, and lacking causes leaf yellowing and browning of leaf tips, Fe makes the chlorophyll synthesis in leaves provides chlorosis, Mn depends on soil pH whereas it hydrates the chlorophyll developing enzymes and lack of Mn creates yellowing materials between leaf veins. Crops use Mo in nitrogen fixation and minimize nitrates to convert them into usable forms. Ni develops the urease which is then converted into the urea for their basic usage in growth and development, while Zn creates crops leaves chlorophyll and develops other enzymes too, while its deficiency creates the short crop growth and, in some cases, longer duration of the growth season and ultimately the crop dies.

1.3.4. Evapotranspiration

Evapotranspiration is measured using the weather parameters such as temperature, solar radiation, wind speed and humidity. Multiple empirical methods estimate the evapotranspiration which showed good results. Some methods compute ETc and ETo are listed in Table 1.4 along with the relevant factors. However, due to a diverse set of weather changes, none of the methods perfectly suits all situations. Many other methods are developed that need a set of data related to weather which is not easily available. The following table (Table 1.4) shows a list of methods to measure ETo and ETc and compares these methods. The Table 1.4 reported by Dastane (1978) considers the main physical parameters driving ET (e.g., solar radiation, air humidity and temperature and wind) and explain the measurement methods of each parameter.

Table 1.4. Comparison of different formulas to evaluate crop evapotranspiration (ETc) presented in different regions of the world (Dastane 1978).

Equation(s) developed	**Considered variables (+)**													**Measured factor(s)**
	Temperature	**Air humidity**	**Dry-wet bulb temperature**	**Day light hours**	**Sunshine hours / Cloud cover**	**Radiation**	**Wind velocity**	**Evapotranspiration**	**Crop data**	**Crop factors**	**Soil factors**	**Correction factors**	**Precipitation**	
Blaney–Morin USA (1942)	+	+		+						+				ETc
Lowry-Johnson USA (1942)	+											+		ET grass field of entire growing season
Thornthwaite USA (1943)	+				+							+		ETc with enough available moisture
Penman UK (1948)	+	+		+	+	+	+			+				ETo / ETc
Blaney–Criddle USA (1950)	+			+						+				CU crop

Thornthwaite-Mather USA (1955)	+				+						+	+	+	ETc with soil water balance factors
Hargreaves USA (1956)	+	+		+						+				Eo or ETc
McIlroy Australia (1961)	+	+	+	+	+	+	+			+				ETc
Olivier UK (1961)	+	+	+		+	+					+		+	Basic crop and land water requirements
Christianson USA (1966)	+	+			+	+	+					+		ETc

ET = Evapotranspiration
CU = Consumptive use of water
Eo = Evaporation from U.S. Class A pan from an open field of grass

Evapotranspiration is the total amount of transpiration from plant leaves and evaporation from the soil surface. The rate of evapotranspiration is managed by three parameters such as crop characteristics, degree of crop cover and growth stage; moisture availability in the soil; and weather parameters which fluctuate the evaporative demand. Potential evapotranspiration (ETp) occurs in the conditions when the soil water is unlimited and the crop is in an active growth stage with complete ground cover; the rate of ETp for the crop type is then majorly governed by the weather conditions. Actual evapotranspiration (ETa) is also known as consumptive water use, and is the actual amount of water lost during crop production by transpiration by crops and by evaporation from soil surface (Dastane et al. 1978).

The values of ETa can reach ETp depending on the weather conditions. It is complex procedure to determine ETa than ETp due to multiple factors. The ETa can be estimated directly by periodic soil analysis and oven-drying; differences in soil moisture by the crop growth are followed and soil layer depletions. The ETp can be estimated from the weather factors such as temperature, wind, humidity, and solar radiation, Multiple empirical equations to estimate the ETp are available. Some equations compute both, ETp and also ETa including all the parameters. None of the empirical equations is perfectly aligned to compute all the required parameters. Some methods are developed that elaborate a set of weather data; however, the data is not available in all conditions. Excessive costs of operations and installation of equipment, time consumption and the particular crop type make it difficult to apply and use these empirical equations in daily agricultural processes (Dastane et al. 1978).

This thesis provides a simple overview of the significant models to estimate evapotranspiration (the models are analyzed for results acquisition in Chapter 3) which is as follows: 1) Hargreaves–Samani (H–S) model; 2) Blaney–Criddle (B–C) model; and 3) Penman–Monteith (P–M) model.

1.3.4.1. Hargreaves–Samani (H–S) model

To compare the performance of ET temperature methods, Allen et al. (1998) reported that ETo can be determined by using the empirical Hargreaves–Samani (H–S) model (Hargreaves and Samani 1985) for estimating the PM-ETo values, which also include using data from local weather station (Allen 1997). Multiple ET temperature determining methods are then omitted – and ultimately are not measured in any study, including the ET estimation using the Thornthwaite (1948) model, that majorly underestimates the grass ETo unlike to the PM-ETo (Allen et al. 1994). In both these methods, the least data required includes T_{max} and T_{min}. The latter method for estimating the PM-ETo using the T_{max} and T_{min} is known as Penman–Monteith (P–M) model. Both the HS and PM models are widely adopted in research comparatively to the use of local meteorological data.

Based on a complex analysis of the literature and applications of the HS model, Hargreaves and Allen (2003) stated that remeasuring the coefficients and exponents of the HS model simply increase the complexion of the empirical method. The HS model is generally preferred from other highly complicated methods as it is reasonably suitable and needs simply minimum and maximum air temperatures (Hargreaves and Allen 2003). It is of importance in zones where air humidity, solar radiation, and wind velocity data are not available or with poor quality, while the minimum and maximum air temperatures are provided in most of weather stations and agro-climatic conditions since air temperature can be calibrated with minimum errors and by less experienced experts than the other needed climate factors used in the equations.

The HS model (Hargreaves et al. 1985) needs only acquired T_{min} and T_{max} values for estimating the ETo (mm day^{-1}) which is followed as:

$$ET = 0.0023 \times (T_{ave} + 17.8) \times (T_{max} - T_{min})^{0.5} \times R_a \qquad 1.5$$

where Ra is known as the extraterrestrial radiation, T_{ave} is the average temperature acquired, T_{max} is the maximum temperature and Tmin is the minimum temperature collected during the during the observation (Samani 2004).

1.3.4.2. Blaney–Criddle (B–C) model

In the conditions where the data of pan evaporation is not available at local scale, an empirical model, such as the Blaney–Criddle (B–C) model (Blaney and Criddle 1950) is used to estimate the reference evapotranspiration (ETo). There are multiple empirical models to estimate the ETo. Most of them have been considered and calibrated on local scale. If these local empirical models are available, they could be tested. In the condition where these local empirical models are not available, the general empirical models could be utilized. The generally used empirical models are the modified Penman model, as described in next paragraph. This model is considered as a little technical but highly efficient. The Blaney–Criddle method is rather simple and can be used by putting the acquired data on temperature only. However, this model is not highly efficient and delivers a generic estimation into the study. Particularly, under extreme environments the Blaney–Criddle model shows inaccurate values: in dry, windy, and sunny areas, the ETo is underestimated about 60%, while in calm, clouded and humid areas, the ETo is overestimated about 40%. The empirical model of Blaney–Criddle is shown as:

$$ETo = p \times (0.457 \times T_{mean} + 8.128) \qquad 1.6$$

where ETo is the reference evapotranspiration (mm day^{-1}), T_{mean} is the mean daily temperature (°C), and p is the mean daily percentage of daytime hours.

1.3.4.3. Penman–Monteith (P–M) model

The FAO Penman–Monteith (P–M) model is considered as the sole ETo model for estimating the reference evapotranspiration. The modified Penman model is now considered to provide the best results with least possible error in conditions of a healthy grass reference crop. The solar radiation method is suggested for regions where available weather data include calibrated sunshine, air temperature, cloudiness, or solar radiation, but not calibrated air humidity and wind speed. The modified Penman model is frequently used to overestimate ETo for about 20% low evaporative environmental conditions. The other FAO recommended empirical models (as aforementioned) provided different values of reference crop evapotranspiration when estimating the standards of healthy grass. The FAO P–M model provides the evapotranspiration of the reference soil surface can be unambiguously estimated, and this model provides consistent ETo results in all climates and regions.

Using the original P–M empirical model, the aerodynamic equations and surface resistance equations, the FAO P–M model to estimate ETo is derived as:

$$ETo = \frac{0.408\Delta\,(Rn - G) + \lambda\,\frac{900}{T+273}\,u_2\,(e_s - e_a)}{\Delta + \lambda\,(1 + 0.34\,u_2)} \qquad 1.7$$

whereas

ETo = reference evapotranspiration (mm day^{-1})

R_n = net radiation at the crop surface (MJ m^{-2} day^{-1})

G = soil heat flux density (MJ m^{-2} day^{-1})

T = mean daily air temperature at 2 m height (°C)

u_2 = wind speed at 2m height (m s^{-1})

e_s = saturation Vapor pressure (kPa)

e_a = actual Vapor pressure (kPa)

$e_s - e_a$ = saturation Vapor pressure deficit (kPa)

D = slope of Vapor pressure curve (kPa $°C^{-1}$)

γ = psychrometric constant (kPa $°C^{-1}$)

The model uses standard climatological records of temperature, solar radiation, humidity and wind speed. To validate the estimation, the weather data is collected at 2 m above the available surface of the green grass, that shades the ground and does not lack water. No temperature-based model is considered to provide perfect evapotranspiration data under all the climatic regions due to reliability in the equation and errors in data management. It is possible that precision agronomic technology under suitable climatic conditions may show the FAO P–M model to differentiate from the times from the actual data of ETo. However, the FAO commission has considered to use the hypothetical reference model as the FAO P–M model to compute the grass ETo when expressing and deriving the crop coefficients.

Chapter 2

Decision Support System Design and Domain

Decision support system (DSS) is an integrated IT platform for gathering data (crop, soil and weather) in real-time via sensors and scouting tools. These data are stored in a cloud and interpret by running the advanced models, and then used to provide information, alarms and support for decision making processes at different levels (researchers, agronomists, farmers, industries etc.). Farm data are entered into the database in order to generate a real-time flow of up-to-date information between the crop, the DSS and the user. Such a system is the perfect tool for traceability of agricultural products and for filling in country logbooks. It is the perfect tool for taking appropriate decisions in the current and future agriculture, characterized by increasing complexity.

Valecce et al. (2019) developed the DSS used in the present thesis. The application has been developed by PoliBa, University of Molise (UNIMOL) and Asepa Energy s.r.l. (Taranto, Italy). This team developed the DSS which present evident beneficial aspects, however, there are two challenges that are faced by the system during its development such as:

The first challenge is related to extreme weather conditions, which besides the crop, may damage sensors (crop, soil, and climatic ones). Eventually, the damaged WSN system needs to be repaired, fixed or replaced. Other sensor equipment should have the similar features and operating system as the previous one which consumes time, effort and technical knowledge. In real world situation, these types of requirements are not always fulfilled. Due to which the scenario creates more technical problems for the technical experts to work with the DSS. The DSS needs to be developed for the agricultural system, as agricultural system is based on a seasonal performance that is relevant to the food growing and harvesting cycles. During or after the crop growing seasons, growers manage their field and crops in new ways so that to be prepared for the upcoming crop growing season. These developments also include to manage the DSS in accordance to crops and field requirements by updating their operating systems, applications and sensor equipment. The logical command approach of the DSS, in this upgrade shows an error on how development of the DSS operating system, application, and sensors equipment would be conducted with having similar functions in the DSS.

While the second challenge is the interoperability of the system. Agriculture field activities are a set of different processes that needs to be analyzed in a continuous pattern. Eventually, DSS is composed of specific sensor and applications that provide various calculations, and analyze them using advanced statistical approaches in field conditions. Such as, an environmental sensor calculates the air humidity, air speed, solar radiation, and other factor data, analyze the data and intelligently decide whether or not and how much to irrigate. A soil WSN sensor collect data for the soil moisture in each 2 minutes and automatically decide the irrigation quantity required for the crops at the specific environmental condition and field. All these WSN sensor equipment transfer the collected data to the installed DSS that assures the inter-operational activities in between the sensor devices and the DSS. These inter-operational activities produce a set of significant data produced by the DSS which could be utilized to take future based intelligent and timely decisions.

Chapter 2 shows an innovative methodology based on the services stack of the DSS which work on the aforementioned requirements. The Section 2.1 describes the situational background as well as the data life-period of the DSS, while in the Section 2.2 it is reported the reasons for working with the stack of service based on DSS. Section 2.3 discusses two important databases NoSQL database and RDBMS database prior to choosing the most reliable one for DSS. The chapter's major delivery is Section 2.4 which shows message queue telemetry transport (MQTT), as the protocol dedicated to DSS, and defines the procedure to analyze the MQTT. Finally, Section 2.5 presents the summary of the Chapter 2.

2.1. Data life-period of the system

The system collects the data and deliver commands accordingly based on that data. It is considered as a vital factor of the DSS. For data management in agricultural systems, data is defined as 'a particular set of information that acknowledge the situational characterization by specifying different factors' (Abowd et al. 1999). Those factors could be related to 'an object, place, or person or any other thing is directly or indirectly relevant to its usage'. Whereas, a factor must be specified for the given data into the system for the command function as "different sets of objects responsible for different functions, and the provided data that help to implement the required task of the field" (Sun et al. 2016). While a function is described as 'a linear relationship between two variables, one dependent and one independent' (Bendadouche et al. 2012). There are two types of mediums which are, advanced-level and basic-level medium. The advanced-level medium consists of qualitative information while the basic-level medium consists of quantitative information collected by different IoT devices. Qualitative information is a data that analyze the object's status like plant health or data collection speed. Quantitative information is considered as the binary digits or digital structure that are indirectly relevant to an object and are not concerned about the status of the object.

An example for understanding the terms, object and medium, is given for a potential analysis. Under a particular environmental condition, a software program received the collected data from field conditions using the wireless sensor network (WSN) field-soil sensors. Thus, the data is transferred to the DSS through the WIFI upon the commands of the DSS about the maize crop needs water. In this particular environmental condition, the maize crops are considered as an object which is direct related to the whole system. The system has to decide when or not to provide the irrigation, which depends on the maize crop, soil and environmental factors. The soil is considered as the second object in connection to the system in this situation. Analysis of the WSN field-soil sensor shows that the soil-moisture is at 123 cbar scale which is considered as a basic-level medium for maize crop plant (depending on the environment). The software application determines the basic-level medium and upgrade it into an advanced-level medium for soil moisture improvement using the reasoning method. The generated advanced-level medium consists of new measurements based on the previous analysis. The previous analysis is taken away from the basic-level medium to avoid any potential problems. The new analysis shows as soil moisture availability is low. This low factor is the status of the object soil. Finally, a third analysis shows that the object plant requires water, upon a command the irrigation is activated.

The data life-period of events related to the DSS model is shown in Figure 2.1. This intelligent DSS works in various stages such as data collection, management, analysis, and functional stage. These stages further consisted of particular methods that successfully implement the practical work done by the system. They work in a series of functions such as their major role is to collect the data from resources, manage the data through their set parameters, and finally evaluate results out of that data. The presented figure (particularly the left side command factors) show data processed for inter- and intra-stages in the DSS model. The intra-stage of the data is the data that is related to the advanced-level and basic-level medium. The inter-stage data and a system-external (such as external data resources or devices) are known to be as information or data.

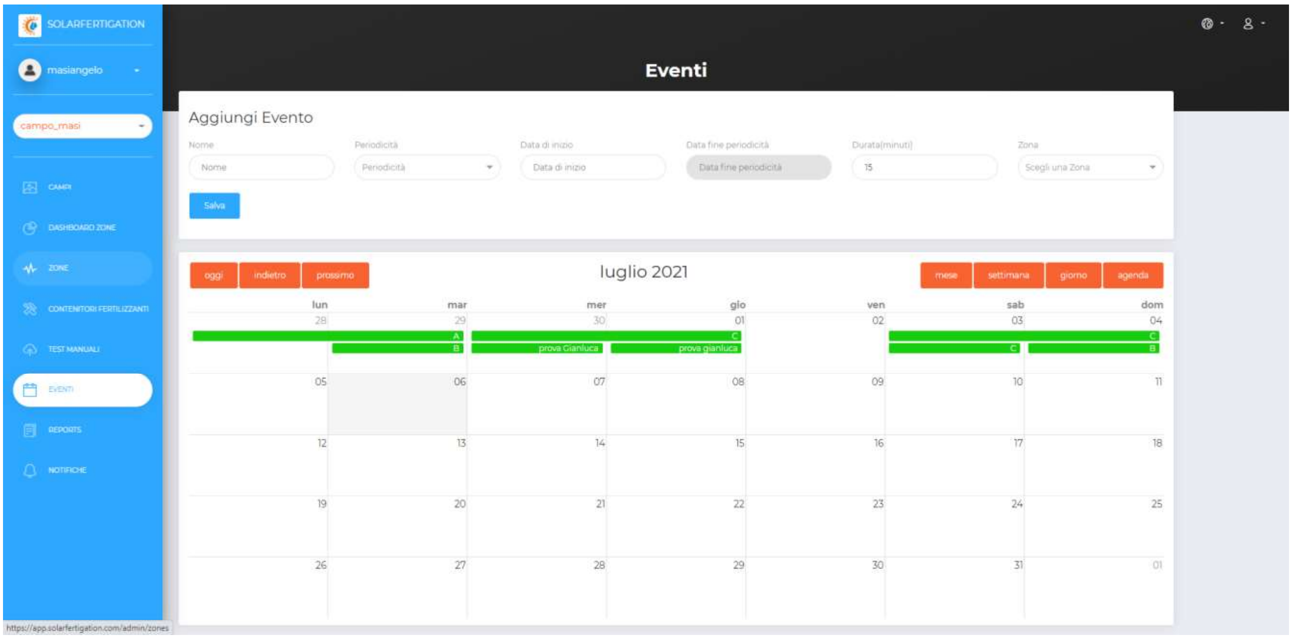

Figure 2.1. The data life-time of different events into an online application of the intelligent DSS model.

2.1.1. Data Collection

A description of the data collection and its methods directly from the WSN devices (or other resources) installed at the field locations is provided. Other resources are considered as those platforms are supported by the Internet with no direct relation with the DSS model. The study shows data management applications which are considered to support the system, for example a WSN-based sensing network supported by various other devices. These devices are known to provide transparent resource data collected from field points. Transparent resource data is particularly utilized for the processing methods for to support system applications.

2.1.2. Management

Data management is a process in which the information is organized in a systematic way into the system. The data organization is backed by the storage data domain. The input resources are provided as transparent resource data in data collection stage. The information into the system preserves the collected data, known as input data, for a longer time with original quality. The system in this stage provides low level medium.

2.1.3. Analysis

After data management, the data requires to be analyzed and transform it into the into the advanced-level medium with logical reasons. The analysis and transformation are recognized by methods which includes fusion, aggregation, and reasoning. Here the basic-level medium is provided as an input from the previous stage for further processing. While the output is provided in the shape of advanced-level medium needed by the system applications.

2.1.4. Functions

A stage where developments related to system utilization of advanced-level medium received after analyzing the data. This is used to run different applications. Three sub-functions are developed in this stage such as action, orientation, and distribution. These three functions provide an output based on data, physical action, and information.

2.2. System design

Developing the system design is a vital process in developing a system. This is considered as a prototype to develop a particular system. Agronomists and system designers prefer a design for the DSS which satisfy their research objectives and required results. System design could be broken down in four types which are considered to be potentially functional and sustainable in field conditions. They are design concept, composition, applications, and system.

2.2.1. Design concept

Design concept is the processes and concepts to design a particular function-based system. Agronomists and system designers have multiple choices to manage and create specific computer software and hardware for their trials with the aim that could justify the limits of the design concept. Micro-service (data transferring), and service-oriented architecture (particular function-based application) are the examples of this process.

2.2.2. Composition

Composition consists different sets of sections. These sections provide support in specific function. During the test period, each section provides particular data followed by a specific organization commanded by the composition. Agronomists and system designers have different options in deciding the software and hardware applications until it justify the properties of sections.

2.2.3. Applications

It consists of different software and hardware running devices that are connected with the main system. The detail consists of a blueprint information delivered by the software and hardware applications, based on which researchers and agronomists decide the trend of conducting the research such as DIMMER, Agri-IoT and others.

2.2.4. System

The system provides configuration setup based on software and hardware devices. Agronomists and system designers test and manage the system in a given environmental condition. A brief structure of a design method is followed with the specific procedure as: design concept, composition, application, and system. Following this procedure, a design method of a system is considered to significant development with modern and sophisticated structure to function and automatically deliver results. The study proposes a design method for DSS with a particular research objective that is feasible in all locations and with every type of system device.

2.3. Comparison of NoSQL and RDBMS database

The database system was managed by the engineering team of the PoliBa at different locations of test fields (Valecce et al. 2019). They made it sure that the system properly transfer data to the database and the database process it for further verification. Two databases were compared to provide an overview about the state-of-the-art of the research. Relational database management system (RDBMS) is utilized due to their efficiency in storing and querying features of large quantity of crop data. While, the conductivity of the RDBMS is considered to be negatively impacted by the various needs and requirements to be fully transactional in a consist way, however those such properties are recognized as atomicity, consistency, isolation and durability (ACID) which guarantees a system. On the other hand, non-relational database, known as NoSQL, are developed to support just what is identified as eventual consist feature to further advance the performance and scalability. An evaluation between the conductance of both, RDBMSs and NoSQL database technologies, were presented by Stonebraker et al. (2010). In this comparison test, a relaxed consist feature was utilized in the relational organization to depress the overhead scheme. This overhead scheme was earlier presented to be divided in an even order in between four structures of the RDBMS (with using the locking, latching, logging, and buffer management) (Harizopoulos et al. 2008). Though, the conductance related to system querying and data persistence has showed a potential to develop by using a simpler consistency system which is not tested in an efficient way for crop management.

RDBMS database are completing their four decades in supporting and developing the traditional simple query language, keywords, and indexing techniques. Though, few modern NoSQL databases were developed for similar query languages, keywords, and indexing utilization so that to acquire the evolution of the RDBMS database (PoliBa research project partner). These databases are also called as SQL-like language query databases. Moreover, related to their SQL-like features, they particularly develop new indexing strategies. The objective of the aforementioned database is to describe a particular standard for the result output of major queries at historical crop and environmental data collected, particularly from the sender system. In addition, the system is focused on exploring the effects of different indexing structures and query output techniques between various consistency stages with two relational databases (SQL) and two non-relational (NoSQL) databases to scale analysis and providing loading results of persistent schemes. The trials were composed of database search engine such as two main RDBMS systems (PoliBa).

There are many factors that are considered to affect the result output of querying, analyzing, and loading the persistent logs such as: 1) indexing techniques, for example first and second index utilization, 2) relax consistent data, and 3) data equivalency at different nodes, for example auto, or manual-shading.

The result output of the trials was a standard such as major queries for analyzing and accessing the crop and environmental persisted data. The features of such queries are as: major search, selection, range and aggregation application. The dissertation provides a valuable discussion on the standard applied to the previously discussed systems.

2.3.1. Background

This section presents the importance of the database managing system for crop database applications and the condition of a persisting log scheme based on crop management from crop and environmental real-time field data. In addition, it presents indexing techniques, database transactions, partitioning (sharing), and consisting stages. Lastly, the changes in relational (SQL) database and non-relational (NoSQL) database that automatically leads to modern NoSQL databases such as Redis (Redis) and Cassandra (Cassandra), and two main relational DBMS are compared on their functions, features and parameters required.

2.3.2. Reasons on database organization

A database is known as the collection of particular data in an organized form. Some researchers have utilized the term database to denote to database system, while many others have mentioned it as group of particular information that is deposited at database (Beynon-Davies et al. 2003). These particular databases are responsible for taking care of the complete dataset and their structure, storage, and are known as database managing systems (DBMS). DBMS communicate with various computer systems, user applications, and other DBMS systems to serve large data management and collection. DBMS are presently protected using different groups such as relational DBMS that support structural query language (SQL or SQL Database), and non-relational DBMS that support not-only structured query languages (NoSQL) (NoSQL Databases). Irrespective of the changes of these two methods, every application in all regions of the world agree on their significance. A standard of result-output between these modern DBMS systems were discussed in this dissertation.

2.3.3. Conditions for application

As discussed in previous section, the study was conducted to investigate and compare a single modern MongoDB, NoSQL databases, with two relational database systems. The study evaluated further two modern NoSQL databases, commercial relational database system and a modern type open-source relational DBMS system. Due to which, the study presented same datasets and applications that were utilized previously. The applications are composed of real-time persisting scheme data within commercial fields in which manual labor was transformed into mechanical under a monitored and controlled setup. Due to which, each sensor of the mechanical system studies the values of each factor such as temperature, pressure, and other significant values. These values are then efficiently transferred into storage system to make sure an optimum performance of large values active in both, writing and retrieving schemes. Database systems for these applications have a group such as table, particularly known as measures. These measures are composed of mechanical factors denoted by (s), sensor denoted by (m), initial time-lapse of reading values denoted by (bt), final time-lapse of reading values denoted by (et), and calculated values denoted by (mv). In this table group, it also consists of a composite key that present three major columns (sensor, machine, and initial time-lapse of reading values). With this style, the signs such as (s, m, bt, et, and mv) are able to receive data related to persisting schemes from large calculations of mechanical sensors.

This large set of data schemes are activated in a bulk form in two modern databases such as Cassandra and Redis, and two other DBMS systems. Upon successfully finishing the loading procedure, there created a different output of main queries for evaluating the persisted schemes. The features of queries are basic search, selection, and aggregation.

2.3.4. Execution

Execution is one of the major functions of a database to preserve the collected data. Execution is composed of different functions to accomplish other database functions, which includes to perform all of the functions or neither of them. The function of a single execution is performed in a proper sequence and upon its completion, the updates are provided and implemented into the database system. This execution could also be rolled-back in particular conditions, which undo all the performed functions of the execution, and is known as atomicity. Atomicity is one of the features of ACID which makes sure that not a single feature of the database execution is left unperformed with an inconsistent sequence. By making sure the execution, researchers and agronomists perform their updates in a single execution with no issues in consistency management. Consistency management is one of the features of the DBMS execution which guarantees the data availability, and validity of system rules in the database which help in keeping the database in a consistent shape.

Researchers and agronomists, in a consistent database system, read/write the data in comparable databases, that run executions, while, every execution has to be conducted once at each time and no execution has to provide any impact on the other. For example, if two executions are performed in a same way with similar values, and if they modify values from the initial execution prior to the second execution with same values, the result outcome of these executions will be affected. This character of locking is known as isolation and is also based on ACID. Though, few applications perform just a single execution at once, and will provide less efficient results. The results outcome of the execution, in this condition, will present that the database has to guarantee the durability of the executions in a way that perform updated tasks in hard conditions. While, this feature is considered to be recover the crash report of the system (Gray 1981).

2.4. Message queue telemetry transport (MQTT)

In 1999, message queue telemetry transport (MQTT) protocol was surfaced for the first time by Andy Stanford Clack (IBM) and Arlen Nipper (Eurotech). In 2013, it was recognized at OASIS

(Locke 2013). This protocol supports to provide a connection for embedded, networks and middleware systems. Moreover, the protocol provides an easy resource to develop new schemes (Boyd et al. 2014). The MQTT was developed based on the TCP scheme. MQTT presents several types such as MQTT-SN, and MQTT v3.1 (Locke 2013). The MQTT-SN protocol provide sensor specific services and suggest UDP-based evaluation of MQTT. The MQTT presents several features such as (Boyd et al. 2014):

1. Provide high connection points for more devices
2. Provide options of optimized connectivity for remote and sensing equipment
3. Provide relevant analysis
4. Provide management and sequential arrangement of the data

The MQTT presents telemetry system to deliver data hurdles related to a diverse set of users. The telemetry system provides analysis and other evaluation in a remote setting. The advancement in the system paved its way to interconnect all analysis at the same platform and control other systems, making it more efficient in result output and cost with high benefits (Lampkin et al. 2012). The telemetric system provide support on remote devices to researchers and agronomists for smart system interactions. The data is important for making decisions by the agronomists, such as crop sensors at the particular time of the day, after collecting the environmental parameters, calculates the exact amount of irrigation need to crops. The data is collected by different sensors installed in the field. Upon accomplishing all the hurdles in using the data protocols for data communication, results could be made available. A hurdle starts after collection of the data using sensors and delivering it to users and third-party resources that need the result. The intensity of this hurdle depends on the geographical distribution, resource potentials, and user availability (Boyd et al. 2014).

The MQTT is composed of subscribers, brokers, and publishers. The subscriber is benefited when the communication is made and the data is communicated to the subscriber. When it is published, the data is transferred to the required user (Stanford-Clark 2013). The MQTT also provide an optimum messaging protocol service supporting the M2M and IoT communicating layers based on limited energy, low-cost, and small memory system for small bandwidth communication systems (Al-Fuqaha et al. 2015).

The MQTT protocol establishes the communication of publisher and user and the user with the subscriber in a proper sequence. This proper sequence let the user, publisher and subscriber to understand the transferred data. For initial communication, a connect message is transferred from the client, subscriber or publisher, to the server, broker, for communicating between each other, the server then sends the Connack message as a response of it. For completing this communication, the publisher transfers a Disconnect message. Three quality of services (QoS) support the initializing, management, and completing (Locke 2010) of this communication process such as, 1) QoS-0, 2) QoS-1, and 3) QoS-2.

QoS-0 is the process in which the data is transferred with best resource using the IP/TCP layer. In this process, the response is not guaranteed. The data is either able to reach or not to the server, while the sender transfers a Publish message for further communication.

QoS-1 is the process in which the communication is occurred in a default mode (Locke 2010). The data is received by the receiver so that the data delivery is guaranteed. Under certain conditions of losing the data, the communication is validated for any leak point, and the data is sent after a specific period of time. In this way, there is a collection of messages that is present with the recipient. The sender system using QoS-1 process transfer a Publish message that consists of message identification codes. The Publish message achieve a phase of unrecognition until the sender obtains the Puback message from the receiver (Locke 2010). Upon the message removal from the sender, the receiver transfers an acknowledgment towards the sender. Both sender and receiver systems remove the received data following proper a procedure.

QoS-2 is a rather established process where a secure layer is used with no loss or disordered messages are received. In this process, a large set of communication takes place as the QoS-2 support to send data with the best quality of service. In this process, the data is assured that a message is received after the receiver acknowledgement. The Publish message in this process consists of two steps. First, it is considered as a recognized process after the sender receiving the Pubrec message. The sender system is considered to send a Pubrel message and wait for the receiving system. Second, the Pubrel message is considered as recognized after the Pubcomp message received by the receiver (Locke 2010).

2.5. Summary

Chapter 2 shows the stack of facilitation for DSS. Stack of facilitation is an application that support the medium life cycle of DSS. This application is based on the micro-service design principle of sixteen facilities. The stack of facilitation for DSS highly upgrade the system functions due to the focus on particular goal. Researchers and agronomists are provided with multiple options to change/replace/upgrade/install new software applications and/or hardware components for better results. The aforementioned considerations and a unique approach highlight that the Chapter 2 provides the necessary resources in developing the DSS. A huge gap is observed in analyzing the crop, soil and environmental aspects using the integration of DSS, and remote sensing systems. Literature findings showed that very little work is available which is not up to the mark. This can potentially upgrade the crop vegetation, yield and production sustainability by connecting skies with the soil using the IoT-based WSN networks. This could be a new direction for agronomists and bio-system engineers in their potential research.

Chapter 2 further present features and functions of the MQTT, a modern communication protocol dedicated to RDBMS database. This database system present storage, receiving and sending communication features based on the different types of computations such as calculation, aggregation, and subtraction and a variety of information including calculated information, aggregated information, and deducted information. The chapter presents other methods that evaluate computational process, for example features and characters of interest. This chapter provide features of databases to develop common evaluating regulations. MQTT protocol utilizes modern database systems such as NoSQL/RDBMS. Upon clearing different trials, the protocol is available for user interface, and the domain developers update and manage the domains by analyzing the relevant GitHub trend. Chapter 2 is concluded in analyzing the available challenges for DSS interoperability. Though, few points need to clarify and must be investigated such as;

1. The available version of the MQTT system provides optimum method for better communication upon calculating, aggregating, and subtracting the information. The system then correlates the calculated information, aggregate, and subtract it for further processing. While, processing within the subtracting and actuating, the correlation from subtracting the information from actuators provides an active status. This type of feature shows significant results within the DSS system.
2. The database systems are not able to show new features related to the DSS, for example coordinates and networks of the DSS. This should be included in future works for the MQTT development.
3. MQTT is a protocol that address problems related to the diverse nature of DSS data. This protocol is a common framework DSS systems. However, the features and characteristics presented some gap which needs to be filled up in relation to swift data description in particular conditions. Such as, for an intelligent field system it is required to have particular soil-moisture data communication, whereas an intelligent irrigation system requires the particular data for crop drought analysis.

Chapter 3

Results – Development of an Agronomic Solar Fertigation system using DSS, Environmental and Crop data

Chapter 3 presents the development of the solar fertigation system, its functions and data utilization. This chapter is divided into three sections. The first section, Section 3.1 shows the solar fertigation structure, integrated with the photovoltaic panels, desktop web-based platform and mobile application, and installation into the fields. The second section, Section 3.2 shows the reference evapotranspiration in relation to the important DSS for irrigation on the market. Section 3.3 shows the irrigation management for the estimation of daily crop evapotranspiration (ETc rainfall and soil). Section 3.4 shows the cdata collected from the crops, and their assessment. Section 3.5 shows the environmental data collection from 2019 to 2021. Section 3.6 shows the data analysis and comparison between the H–S and B–C models for ETo calculation at all the four stations in Campobasso. Section 3.7 shows the data analysis and comparison between the H–S and B–C models for ETo calculation at all the three stations in Apulia region. While the final section, Section 3.8 shows the summary of the Chapter 3.

3.1. Solar fertigation system

Figure 3.1. Central unit of the solar fertigation system connected with the internet of things (IoT) with the help of wireless sensory networks (WSN) at crop field conditions.

The project solar fertigation system was initiated by an Italian based company Asepa Energy s.r.l. (available here). The innovative system, developed into our project, is a self-sufficient fertigation system backed by photovoltaic energy and a low-cost WSN to collect crops data directly and to support farmers in decision making processes (Figure 3.1). The developed system is focused on to further support a rational use of water and fertilizer resources, and consequently a boost in sustainability. The solar fertigation system provides the integration and optimization of the crops and environmental parameters with the current innovative technologies by both receiving and processing the data from WSN sensors (Figure 3.1).

A solar fertigation system is a sophisticated, computer-based application that help agronomists in implementing accurate, intelligent and time-based decisions (Mahadevan 2003). The system performs different functions aside from retrieving and storing the data such as developing the retrieval functions and information accessibility. The solar fertigation system is able to deliver a significant amount of help to manage a variety of crops in a variety of field conditions such as managing practical problems.

The traditional system has recorded two major limitations. First, this needs day to day monitoring, which have to be performed by the growers. This monitoring is considered as an unstable task as the human error possibility is high as this is highly dependent on growers. Second, the resource limitation problem requires to use water in a sustainable way. A solar fertigation system intelligently addresses both of these limitations. To overcome the first problem, the wireless sensor network (WSN) observes the crops in an accurate and automatic mode that limit the manual work load, with highly precise results using the WSN. To overcome the second problem, the solar fertigation system automatically monitors the data and measure the calculate amount of irrigation amount. The value presented by the system is a precise value based on accurate irrigation application and irrigation intervals for different irrigation methods at field conditions. The utilization of the solar fertigation system is a reliable and efficient option for various fields, integrated with WSN in irrigation management, and has proved to be productive than the custom methods.

The solar fertigation system calibrates the periodicity and amount of water and fertilizer needed (as shown in Figure 3.2) in various crop growth stages while sensor data estimate the humidity and temperature of both, air and soil. The WSN sensors are installed directly on the field and collects the crop, environmental and soil data and send it to a central control unit. The central control unit then analyzes the collected data according to the crop, agronomic and meteorological parameters requirements (Visconti et al. 2020).

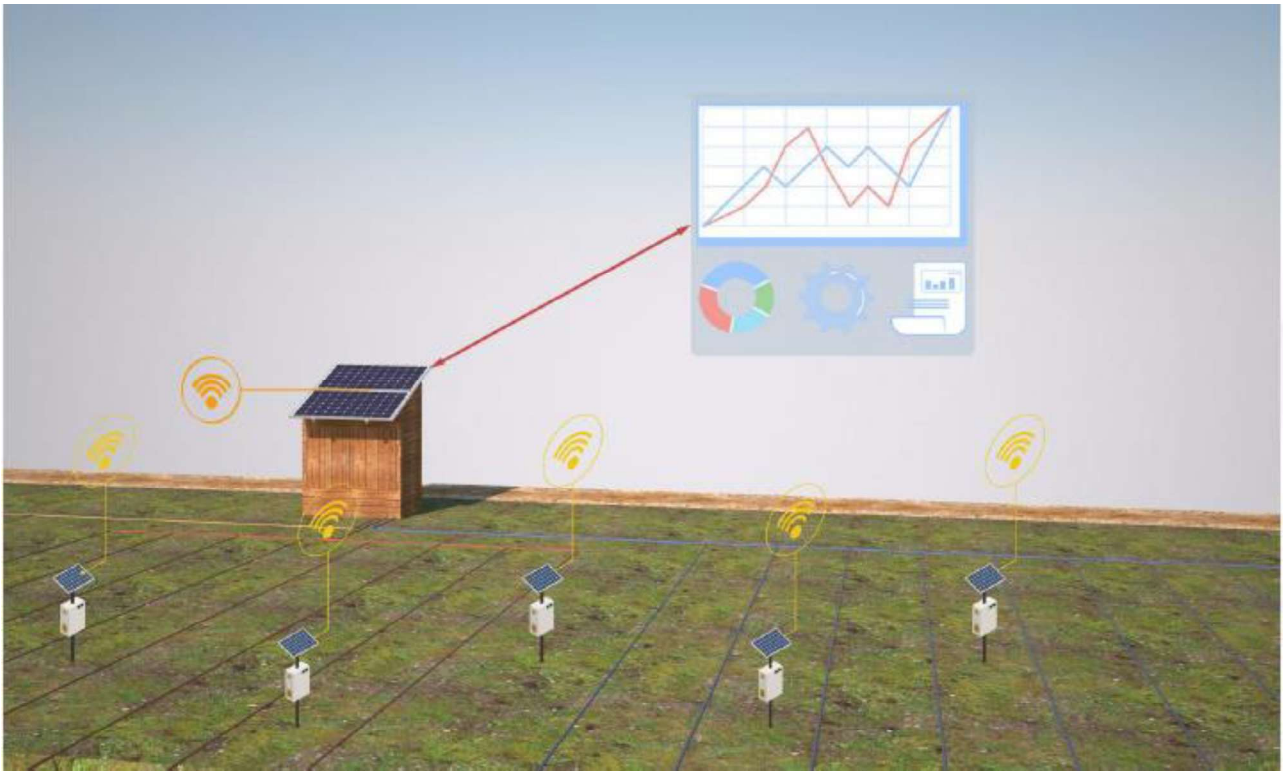

Figure 3.2. Photovoltaic panels installed at the top of the central unit of a solar fertigation system at the crop fields which provides power to the unit for fertigation purposes.

Figure 3.2 shows that the electricity generated from the photovoltaic (PV) panels are transferred to the mixing system which is present inside the central unit, providing an additional profit to the user, or utilized for powering environmental control appliances of the similar field, thus developing a better environmental sustainability in agricultural production (Esen and Yuksel 2013). Most studies have tested the low shading PV panels on the crops, which are not actually common in large fields. The system is considered to provide large-scale investments to maximize the sustainable crop production. Due to which, most PV panels covers 50% or complete 100% of the central unit's floor, without optimally considering the sunlight requirements of the cultivated crops (Vats and Tiwari 2012).

The collection of data ranges from crop, soil and environmental factors, while irrigation and fertilizer are vital parameters to run the system in trials. The table shows various levels of irrigation and fertilizer requirements into the trials.

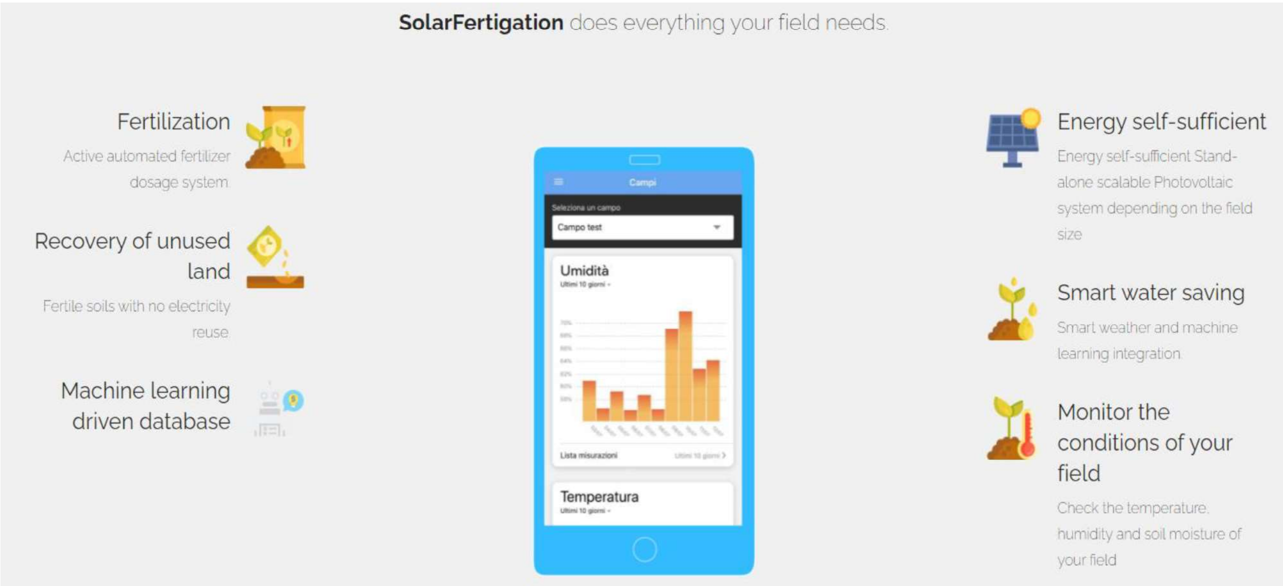

Figure 3.3. Mobile application-based solar fertigation system which controls and monitors the experimental setup at crop field conditions.

Mobile application (as shown in Figure 3.3) estimates the required amount of fertigation parameters based on both crop characteristics and crop type. Particularly, this application support user to conduct their required fertilizer management tasks to ensure optimal conditions for crop growth and production, and water and fertilizer management simultaneously. Moreover, the application also supports the simultaneous management of multiple crops by means of persistent databases. Thus, using this app will provide users with a concrete support for decision-management in water and fertigation management for a diverse number of crops in field conditions.

3.1.1. Web–based desktop platform

This section highlights our web-based desktop platform which received the initial data transferred from the field conditions, managed and processed, analyzed and illustrated in a simple and user-friendly way. Our tests included different fields, crops, environmental conditions, irrigation hours, soil humidity, fertilizer amount, and their problems to solve. Our web-based desktop platform showed the problems and suggestions in a timely and efficient way so that those were addressed in a timely manner without having a higher amount of irrigation or damaging the crop.

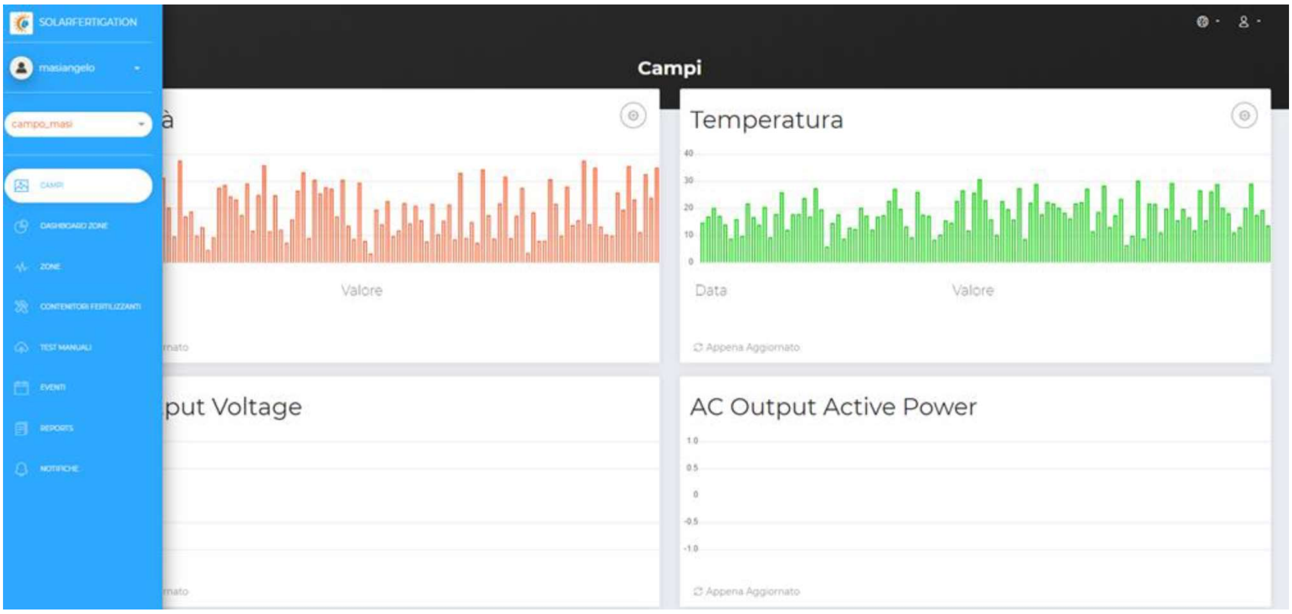

Figure 3.4. Our web-based desktop platform shows temperature (minimum, maximum and average), relative humidity, power controllers and the voltage (input and output) of the system at different fields in trials. The data is collected by the official resource and our system from the years 2019-2021.

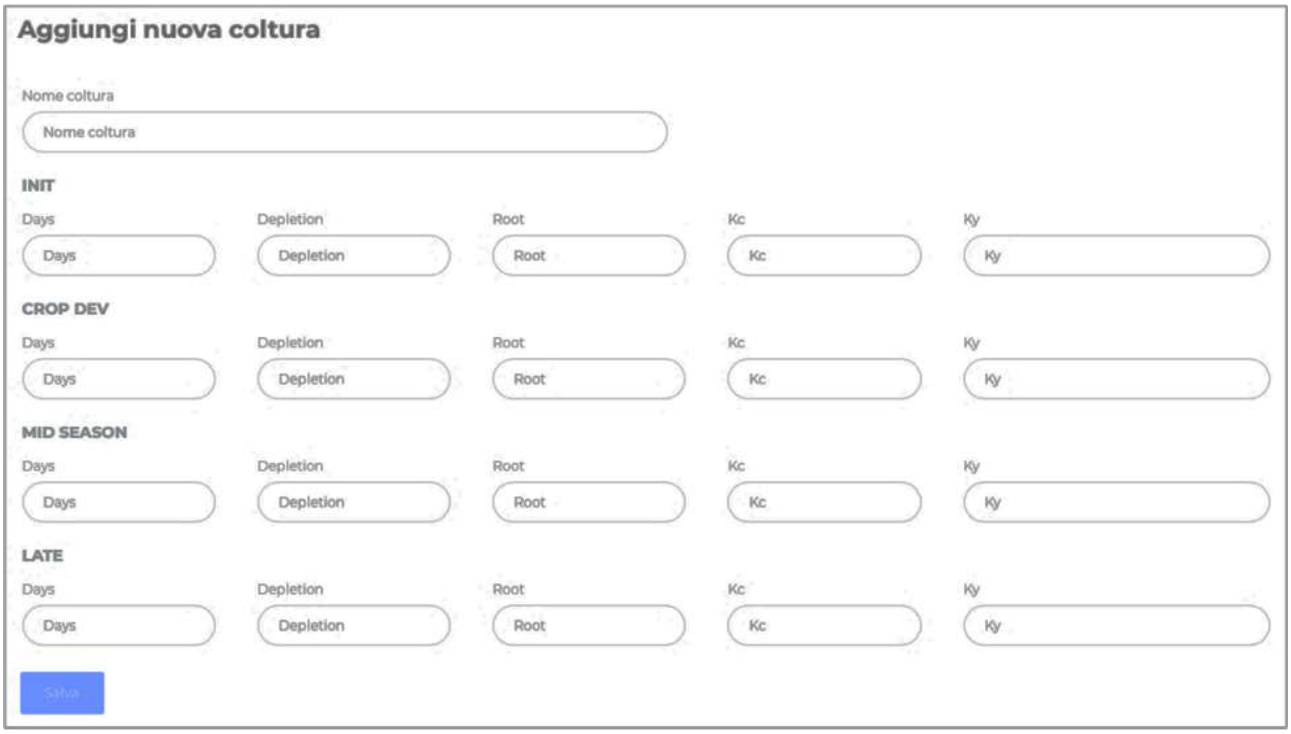

Figure 3.5. Our web-based desktop platform shows the data recorded for each crop, data process and analysis of the crop types.

Our collected data (shown in Section 3.4. Crops Assessment) related to the crop parameters was installed into our system and data for each parameter was recorded for each crop. The initial growth stage, crop developmental stage, mid-season stage, and late stage of each crop was noted by our system and installed, while days to complete, root depth (m), crop coefficient (kc), and crop yield factor (ky) was recorded by our solar fertigation system as shown as in the Figure 3.5. For example, the Initial days for the Tomato crop were recorded as 30, depletion factor (p) as 0.3, root depth (m) as 0.25, crop coefficient (kc) as 0.6, and yield factor (ky) as 0.4. At the Developmental stage, the days revealed were 40 and yield factor (ky) as 1.1. At Mid stage, the days recorded were 45, depletion factor (p) 0.4, crop coefficient (kc) 1.15, and yield factor (ky) as 0.8. While at the Late stage, the days recorded were 30, depletion factor (p) 0.5, root depth (m) 1.0, crop coefficient (kc) recorded from 0.7 to 0.9, and yield factor (ky) as 0.4.

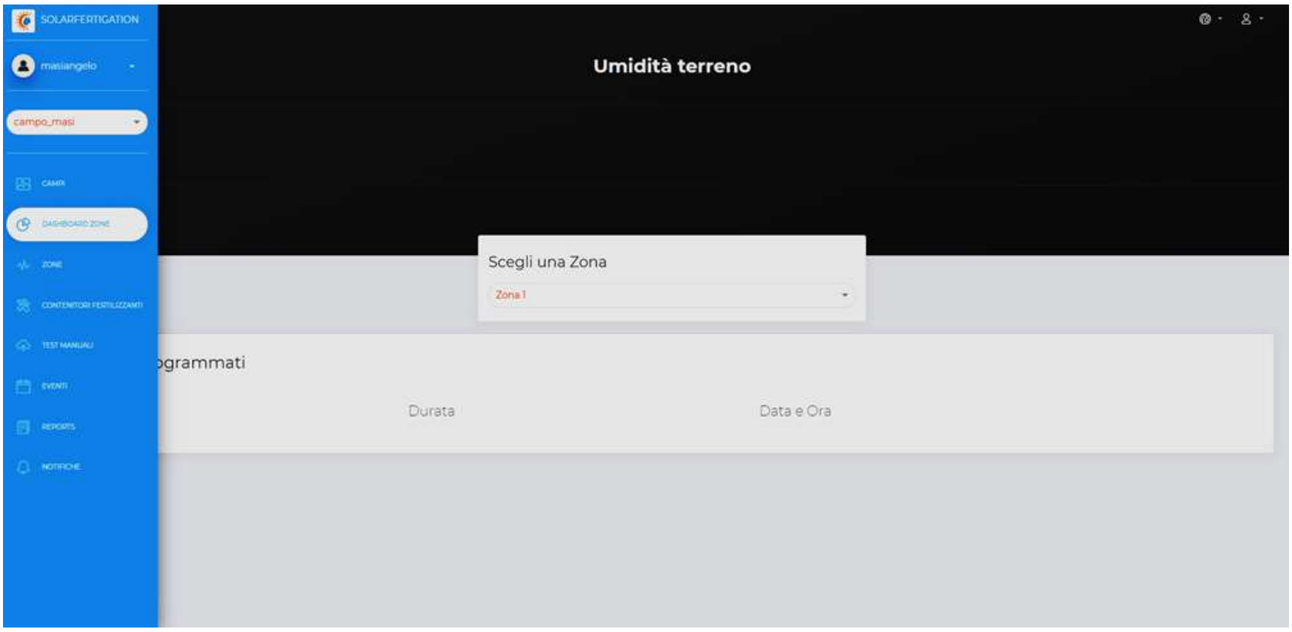

Figure 3.6. Our web-based desktop platform shows the daily soil moisture humidity data.

The data is collected by our installed sensors in field conditions, transferred to the central unit of our system with the help of the wireless sensory networks, processed and analyzed by our web-based desktop platform as shown here. The soil sensors estimate the amount of soil moisture, particularly water in the soil. These sensors are stationary such as handheld probes and are placed at the pre-determined positions and depths in the farm. Installing a soil moisture sensor to a microcontroller or simple relay develop the process into an intelligent and smart irrigation system that estimates irrigation periods and considers the soil moisture conditions, such as the rain periods.

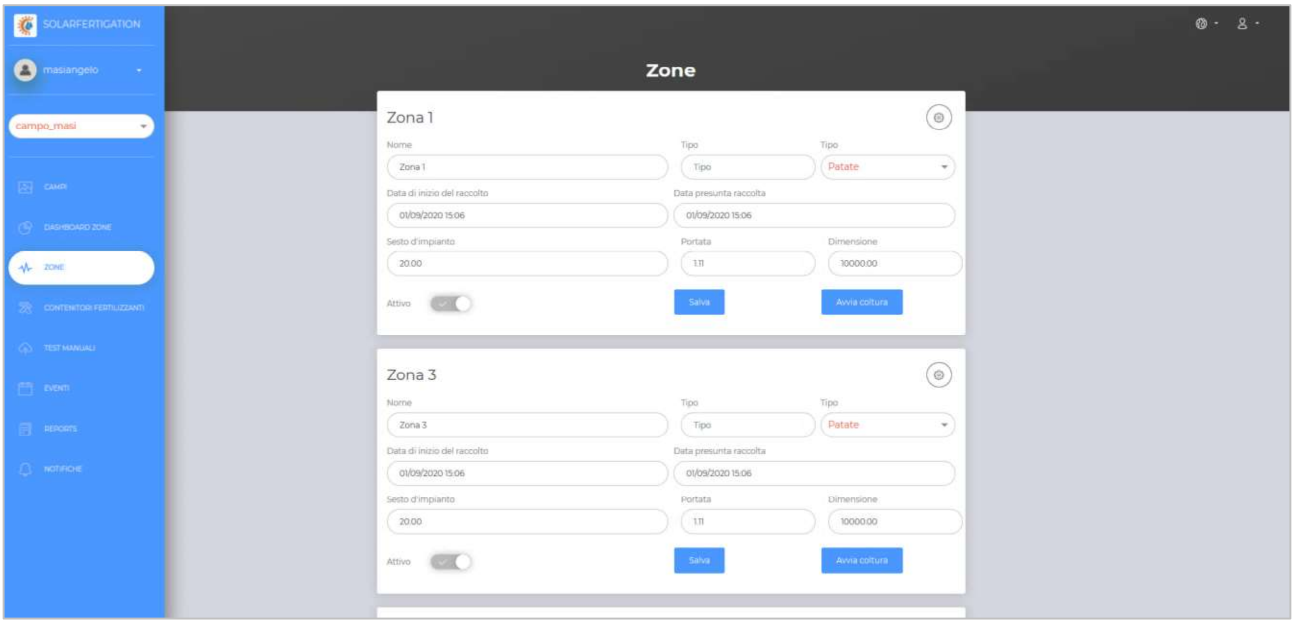

Figure 3.7. Our system is able to simultaneously analyze three zones with different crops, and has the ability to analyze the same crop at the three zones with different parameters as shown here.

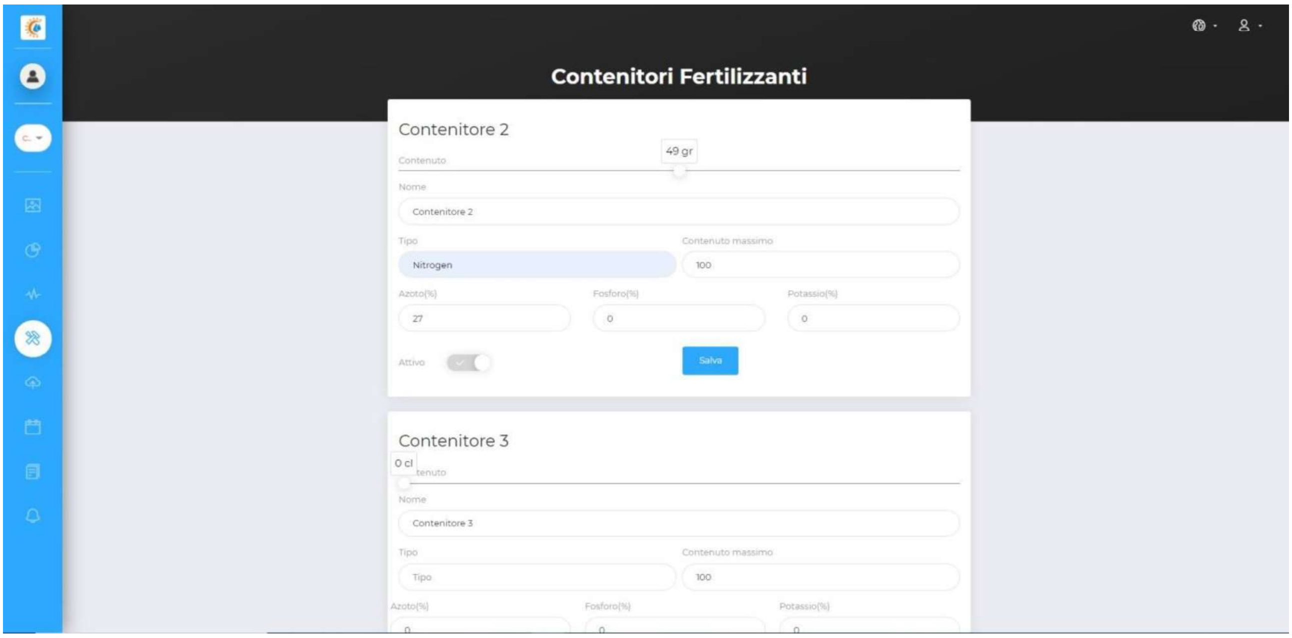

Figure 3.8. Our system processed the fertilizers and irrigation at different field zones during the trials as shown in the above figure. Fertilizer levels and other relevant factors that are currently available in the container for a potential disposal are shown in the containers which could be managed using the web–based desktop platform.

Figure 3.9. Our system shows the ability to automate and/or manual the monitoring and assessment processes. This has the potential to either automate and/or manualize only few processes at the same time in different fields as shown in the figure.

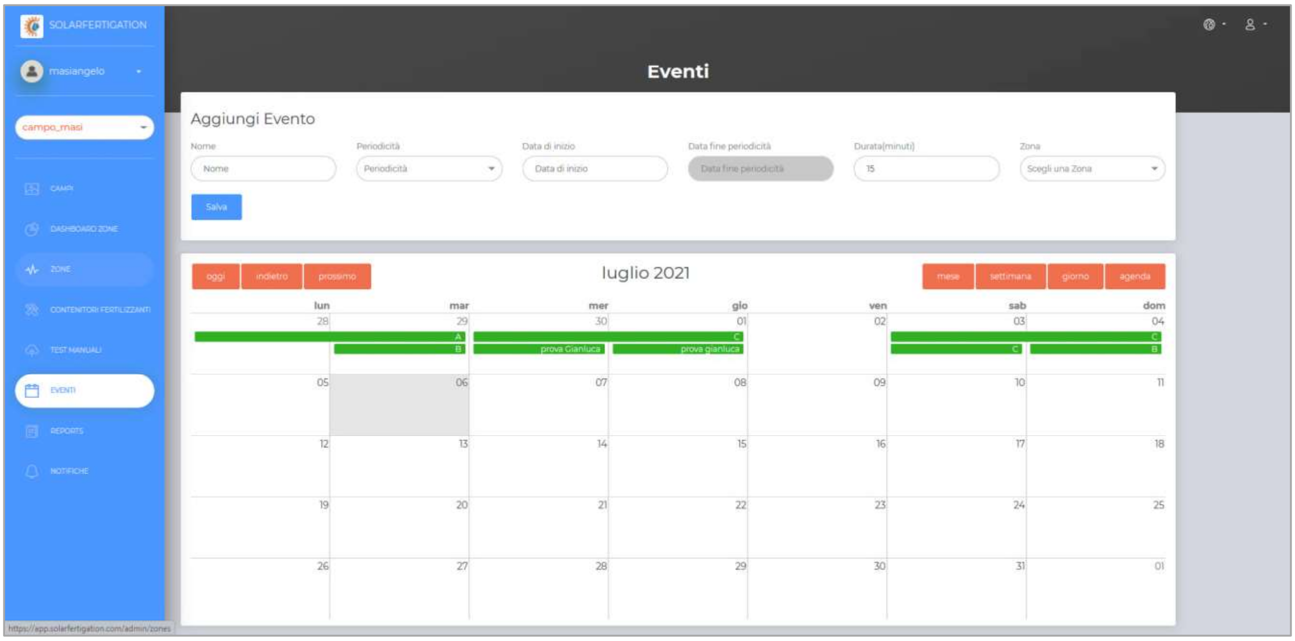

Figure 3.10. Our system shows different events that are completed, continued, and/or will initiate at their particular time in a flowing sequence and provides an opportunity to be updated by users accordingly.

The events include the irrigation periods which were based on the variation in reference evapotranspiration (ETo) and to the change in soil temperature (Ts) and atmospheric temperature

(Ts/Ta) from lower than 1 to higher than 1, the latter was considered as a means to estimate the event transition. Rainfall events were collected which were based on weather data and managed by the desktop web-based platform. The event reflects the amount of precipitation received in correlation to the particular field and timeframe.

Eventi Programmati

Nome	Durata	Data e Ora
prova	1 minuti	01/09/2020 15:58
prova	1 minuti	01/09/2020 15:59
prova	1 minuti	01/09/2020 16:02
Irrigazione	60 minuti	11/10/2020 17:00
Irrigazione	60 minuti	12/10/2020 17:00
Irrigazione	60 minuti	14/10/2020 17:00
Irrigazione	60 minuti	15/10/2020 17:00
Irrigazione	60 minuti	16/10/2020 17:00
Irrigazione	60 minuti	17/10/2020 17:00
Irrigazione	60 minuti	18/10/2020 17:00
Irrigazione	60 minuti	02/10/2020 17:00
Irrigazione	60 minuti	03/10/2020 17:00
Irrigazione	60 minuti	11/10/2020 17:00
Irrigazione	60 minuti	12/10/2020 17:00
Irrigazione	60 minuti	13/10/2020 17:00
Irrigazione	60 minuti	14/10/2020 17:00
Irrigazione	60 minuti	15/10/2020 17:00

Figure 3.11. Our system displays all the events happened such as irrigation, detection, irrigation, fertigation, drought conditions, kc, ky, soil moisture condition values and other environmental activities collected by our installed sensors and solar fertigation system at their particular time-period.

3.2. Reference evaporanspiration (ETo): Important DSS for irrigation in market for P–M, H–S and B–C estimation

Conventional irrigation schedule assumes a fixed daily amount of water following the recommendations of the FAO. Crops require a particular amount of water (mm/day) during the growing season. According to Mason et al. (2019), the conventional irrigation strategy provides

1.8 mm of water every three days. However, it is impossible to provide exactly 1.8 mm of water in real-time and the farmer would likely provide more water than this each irrigation application.

Our system was connected with the soil moisture sensor to continuously monitor, collect and transfer the data for precise water allocation. There were different sensors installed into the fields near the plant root zone. The function of the soil moisture sensor was to enable the scheduling of the irrigation events using an efficient way by either decreasing or increasing the intensity and/or frequency, preserve the important nutrients, and on the other side, provide a thirst factor to plants at their particular stage of growth. Our remote soil moisture sensor empowered the users to manage the water levels without any requirement to the physical presence in the field. Our soil moisture sensor, installed in fields, correctly measured the accurate level of soil moisture. These sensors were integrated into our irrigation system which aided in scheduling the irrigation supply and distribution in an efficient method. The soil moisture sensors used into our study significantly helped in reducing the irrigation amount for optimum crop growth. Our installed soil moisture sensors were integrated with monitoring applications displayed at the desktop platform which are user-friendly and available on many devices, such as PC, a laptop, mobile phone or tablet. Thus, users were able to know about the activities on the farm anytime, which were connected with the internet 24/7. Such applications enabled this study to calibrate the problems in a remote way and addressed it in a timely manner.

Rao et al. (2007) developed a web-based DSS for the management of USDA Conservation Reserve Program. Other studies are conducted on Gpfarm DSS (Shaffer and Brodahl 1998), Modsim DSS (Fredericks et al. 1998), Rwm-Crss DSS (Rajasekaram and Nandalal 2005), ENSO-based irrigation DSS (Paz et al. 2007), IDSS-C (Giordano et al. 2007), spatial DSS (Alrayess and Ulke 2017), and orthodox DSS (Khadra and Lamaddalena 2010). All formulated DSS assist the water management in a timely manner. Acharya et al. (2016) studied a graphical user interface and generated spatial maps for irrigation zones of the field in the Lakhnouta minor, Sidholi Distributary of Upper Ganga Canal System.

3.3. Irrigation management: Estimation of daily crop evapotranspiration (ETc rainfall and soil)

Reference evaporanspiration (ETo) is a complex terminology that defines the conceptual procedures of water losses into the atmosphere through transpiration and evaporation from the crop canopies which depends on the plant and soil type, land cover, and environmental conditions. ETo from a particular vegetation surface is a function of local climatic supporting the evaporative demand that could be used to predict ET for a wide range of vegetation and surface conditions with the help of crop coefficients for agricultural areas (Allen et al. 1998). P–M formula is a reliable calculation formula for ETc supported by the radiative balance that enables the quantification of soil and environmental influence on the evapotranspiration methods specifying the functions of solar energy in the transfer of water from the soil to the atmosphere. The P–M formula provides accurate ETc values in many regions and climatic conditions (Allen et al. 2005), and is utilized globally without the need for additional parameter requirements. The model is well documented, implemented, widely validated and, if compared with other models, this model has been considered as the most accurate model for ETc estimation (Adeboye et al. 2009; Paredes et al. 2018).

Among the P–M, H–S and B–C models, Waller et al. (2016), Zhang et al. (2021), Abdelfatah et al. (2021), Khan et al. (2021), Ding et al. (2021), and Guo et al. (2021) have used the P–M model for the estimation of the ET. The P–M estimates the ET at the standard climatological measurements of sunlight, air temperature, humidity, and wind velocity. Khan et al. (2021) tested the P–M model in Al-Qassim region of Saudi Arabia. Their study processed the climatic location, crop characteristics, sowing and harvesting periods, and soil information in the web-based desktop platform. After the data installation into the desktop platform, they calculated ETo using the P–M model and effective rainfall. The crop water requirement data for maize, wheat, rice, citrus, and barley were analyzed and resulted recorded using the desktop platform. The crop data such as crop's technical name, critical depletion point, crop sowing and harvesting periods, kc levels, rooting depth (m), yield response function at different growth stages (such as beginning, growing, mid-season, and late-season), number of days (total) required for completion, and crop height (m) were also processed and analyzed into their study. Elhag et al. (2021) estimated the crops water requirements using the P–M model. The climatological data and crop kc values were used in the estimation of ETo. Other parameters such as crop water requirement, effective rain, irrigation water requirement and optimum water supply were processed, estimated, and preserved in the desktop platform. Significant data were revealed using the P–M model for crop water requirements for cotton, sorghum, groundnut, and wheat such as 4100 m^3, 3076 m^3, 4103 m^3, and 2473 m^3, respectively.

Our system collected data fits properly for many models based on which, our study recommends to use the P–M model for accurate and precise data management. However, the main limitation of the P–M model is the estimation of a huge amount of climatic data (e.g., air temperature, windspeed, relative humidity and solar radiation) that are not always available in every climatological condition. Due to this limitation, the P–M model is considered as the most difficult model to estimate the ET. The availability and accuracy of weather data for radiation, relative humidity and wind speed may be imperfect in many parts of the world, especially in developing countries of the world. This limitation compelled users to develop simpler models where only data on air temperature (min and max), and extra-terrestrial radiation are needed, such as H–S (Berti et al. 2014) and B–C (Blaney and Criddle 1950) models. If some parameters are not available, the data and the trend analyzed into our study recommends to install the B–C formula into the DSS for efficient processes. Archana et al. (2021) tested the B–C model for the ET estimation on weekly basis. The collection of parameters such as temperature, wind speed, relative humidity, and sunshine hours supported the ET to be higher in the 51st and 52nd weeks of the test in rather of the previous weeks. Alamanos et al. (2021) classified 12 classes of crops and tested for ETo using the B–C model. The utilization of the B–C model showed that the crop water requirement was increased by the relevant losses of the crop coefficient values and the irrigation potential, as found from different surveys (Hydromentor 2015). The ET was estimated according to the irrigation supply and demand with a significant trend. Studies of Goh et al. (2021) depicts that the data and analysis obtained using the B–C models showed values above all the other models indicating the overestimation of the ET level. If the values were not available for the B–C model, our study recommends to install the H–S formula into the DSS for high precision results. The H–S model provide good results to be obtained using the least required environmental parameters for the ETo estimation such as the temperature (Tegos et al. 2015, 2017; Xu et al. 2002; Shahidian et al. 2012). Gentilucci et al. (2021) assessed the interpolation to obtain the monthly and annual crop ETo using the H–S model. The independent variables showed the highest correlation result while the geographical variables were among the lowest (such as latitude, exposure, slope, distance from the watershed line etc.). Dashtabi et al. (2021) estimated the crop ET using the H–S model to verify the values recorded by the web-based desktop platform. The study tested the three wheat fields with optimum irrigation management and estimated the economical and physical wheat productivity. Results recorded economical productivity (NBPD) as 13000 Rls m^{-3} and physical productivity (CPD) as 1.6 kg m^{-3}. Wu et al. (2021) tested the ETo estimation using the several models of the H–S formula on daily and monthly basis. Based on the results, optimized H–S models showed more accurate and highly precise results than the empirical models. The R^2 value for the H–S based estimated ETo were recorded as 0.83, 0.83 and 0.82 while RRMSE were recorded as 0.24 mm d^{-1}, 0.25 mm d^{-1} and 0.25 mm d^{-1}.

The system description and the layout (as shown in the above section) was installed with the data collected from the field conditions. The system was then run on the collected crop data which is shown in the following section.

3.4. Crops assessment

The following collected data shows its integration and installation into the solar fertigation system while different crop data and parameters were installed into the system for efficient management. The aim of this section is to illustrate the data on nine significant crops, crop water requirement, fertilizer requirement, stages of development, stage length (in days), depletion coefficient (p), root depth (Zr), crop coefficient (kc), yield response factor (ky), and bibliographic database for crop water productivity, as shown in Table 3.1.

Table 3.1. Different levels of irrigation and fertilizer nutrients utilized by different researchers in trials (FAO Land and Water).

Parameters	**Fertilizer Requirements N-P-K (kg ha^{-1})**	**Irrigation (mm year^{-1})**	**References**
Citrus (*C. sinensis* and *C. limon*)	100-35-50	900-1200	Chaudhari et al. (2016)
Olive (*O. europaea*)	200-55-160	400-600	Sary and Elsokkary (2019)
Soybean (*G. max*)	10-15-25	450-700	Shen et al. (2018)
Potato (*S. tuberosum*)	120-50-125	500-700	Soratto et al. (2020)
Cabbage (*B. oleracea* var. capitata)	150-50-100	380-500	Sikura et al. (2020)
Onion (*A. cepa*)	60-25-45	350-550	Mubarak et al. (2018)
Pepper (*C. annuum*)	100-25-550	600-900	Youzhe et al. (2016)
Tomato (*L. esculentum*)	200-250-250	400-600	Geisseler et al. (2020)
Watermelon (*C. lanatus*)	80-25-35	350-400	Kang et al. (2020)

3.4.1. Citrus (*C. sinensis* and *C. limon*)

Citrus originated in Southeast Asia and is a perennial tree crop. Citrus world production is 98.7 million tons (fresh fruit), following 62 % orange (*C. sinensis*), 11 % lemon (*C. limon*), and the production of oil and citric acid (FAOSTAT 2001). Citrus tree crops start fruiting from its third year, but significant yields could be achieved from its fifth year. The natural fall of the weak and young fruits is known as "June drop" and "December drop" in the northern hemisphere and in the southern hemisphere, respectively. De-greening of fruit appears while experiencing the cold climate. Citrus fruits take 7-14 months to harvest while lemons, *C. limon* take a longer time than this timeline. The amount of acid minimizes during the ripening stage while sugar and aromatic matters maximizes with the maturity stage. Citrus tree crops can be grown in the temperature ranging from 23-30 °C followed by 13-20 °C of soil temperature for an active root growth development. Flowers and young fruits sheds-off with strong winds and with the temperatures lower than 0 °C. Perfect soils (with soil pH 5-8) to grow citrus are the aerated and deep soils where plant roots can penetrate till 1-2 m in search of nutrients (magnesium, zinc, copper and manganese) and water, while high water-table can be harmful to citrus trees.

Citrus fertilizer needs

Citrus tree crop fertilizer requirements are 100-200 kg ha^{-1}, 35-45 kg ha^{-1} and 50-160 kg ha^{-1} with N-P-K soluble nutrient fertilizers, respectively. Bhite et al. (2017) studied orange, *C. sinensis* crops with a greater cost benefit ratio (1.61) by using 40% N (of the total recommended dose of fertilizers (RDF)) in the crop stage I (Jan-Feb) and stage II (March-April), and 20 % in stage III (May-June). The ratio of P_2O_5 was 50 % in stage I (Jan-Feb) and in stage II (March-April). While 50 % K_2O was used in stage III of the *C. sinensis* (May-June), and 25 % in stage IV and V (July-Aug and Sept-Oct). Studies record that the fruit weight and quantity $tree^{-1}$ increase by using the NPK in a proper amount. While the quality including ascorbic acid content, fruit girth and juice, and reducing and non-reducing sugar maximizes by using the multi-micronutrients for the *C. sinensis* (Chaudhari et al. 2016).

Table 3.2. Citrus soluble fertilizer taken up at different growing stages (FAO Land and Water).

Percent of recommended dose of fertilizers (RDF) to be supplied through soil application for the orange crop																	
Growth stage																	
I (Jan-Feb)			**II (March-April)**			**III (May-June)**			**IV (July-Aug)**			**V (Sept-Oct)**			**VI (Nov-Dec)**		
N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
40	50	0	40	50	0	20	0	50	0	0	25	0	0	25	0	0	0

Gawali et al. (2019) suggests for the *C. limon* at 120 kg N, 40 kg P_2O_5, and 40 kg of K_2O $hector^{-1}$ is a moderate quantity. A little amount of N with greater amount of P_2O_5 and K_2O at the time of plantation (during first year), while the remaining N is applied in four-equal-splits after each harvest of the fruits. Behura et al. (1998) studied the *C. pendulus* and recorded that higher plant height, tiller number and herb yield were found by using the fertilizer amount following the rates of 100 kg, 50 kg and 50 kg of N-P_2O_5-K_2O ha^{-1}, respectively. Mirzajani et al. (2019) studied the fertilizer application doses for the Lemon Balm (*Melissa officinalis*) with the chemical fertilizers of 90 kg ha^{-}

[1] urea (CH_4N_2O), 90 kg ha^{-1} triple super-phosphate (Na_3PO_4), 90 kg ha^{-1} of K_2SO_4 while the treatments utilized with the fertilizers at 100 kg ha^{-1} revealed best results in all treatments showing the yield of 0.13% of essential oil contents, 4808.2 kg ha^{-1} of biological yields, and 1.54 mg gr^{-1} FW of total chlorophyll content.

Adams et al. (2019) claimed that soil salinity significantly affects crop growth while higher NaCl content declines plant development and negatively affects many plants physiological processes including chlorophyll contents, and stomatal conductance. While mild concentrations of NaCl (30 mm) applied to plants provide higher biomass and photosynthetic potential. A study used the water balance approach of FAO 56 manual using fluxmeter and found that 37%-45% of irrigation water is wasted by deep percolation due to an increase in over-irrigation and reducing the soil salinity to leach all the present soil salts (Nassah et al. 2018).

In general, reproduction of citrus trees is performed through transplantation but in many cases, they have also been propagated through bud grafting, while plant to plant distance ranges from 4 × 4 to 8 × 8. The density of the plantations ranges from 200-800 trees ha^{-1} with the legume crops intercropping technique.

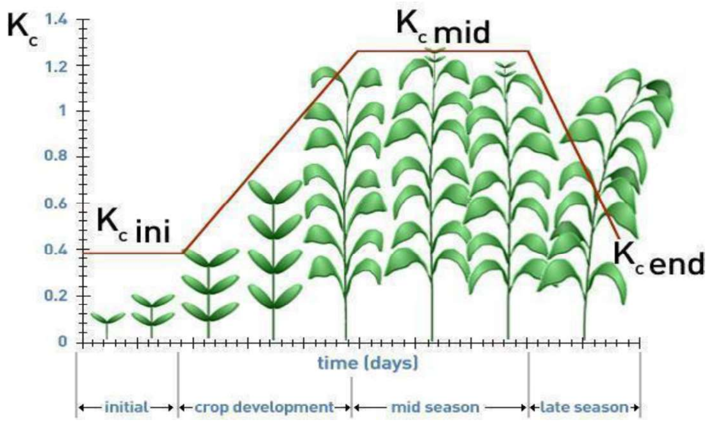

Figure 3.12. Different citrus crop stages from initial, crop development, mid- and late-season development stages against the day's length and crop coefficient, kc (FAO Land and Water).

Table 3.3. Citrus major crop coefficients significant for the crop production and yield growth parameters (FAO Land and Water).

Stages of development						**Plant date**	**Region(s)**
Crop characteristics	**Initial**	**Crop development**	**Mid-season**	**Late**	**Total**		
Stage length (in days)	60	90	120	95	365	Jan	Mediterranean
Depletion coefficient (p)	-	-	-	-	0.5		
Root depth (Zr) (m)	-	-	-	-	1.2		
Crop coefficient (kc)	0.7	>>	0.65	0.70	-		
70% canopy	0.65	>>	0.60	0.65	-		
50% canopy **20% canopy**	0.5	>>	0.45	0.55	-		
Yield response factor (ky)	-	-	-	-	0.8-1.1		

Crop water needs

Total Water demands range from 900-1200 mm year^{-1} (but depends on soil and weather conditions, development stage and daily ET rate of the region), as they are evergreen plants. Er-Raki et al. (2018) modelled seasonal actual crop evapotranspiration (ETa) of oranges based on the modified Penman–Monteith equation by using drip irrigation method in semi-arid region. The comparison results in-between measured and modelled ETa revealed that the proposed model truly and precisely provides the ETa with the error potential of < 20%. A study conducted by Abdelraouf et al. (2020) shows that increasing rice straw amount, application of the partial root-drying technique, and by providing 100% of the Water demands, this leads to enhancing the productivity, quality and water use efficiency of the orange field crop.

Table 3.4. Citrus tree monthly crop coefficients (kc) for the ETm and ETo (FAO Land and Water).

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
70 % crop canopy	0.75	0.75	0.7	0.7	0.7	0.65	0.65	0.65	0.65	0.7	0.7	0.
No control of weeds	0.9	0.9	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85

Water availability and yield production

During the water stress conditions, the plant growth stops, fruits prevent maturity, leaves curl up and the tree fruit and plant provide minimum quality. While soil water depletion leads to adequate water deficits in yield formation and ripening stage which positively affect the fruit acid and results in an increase in the soluble solid contents. The plant’s vegetative growth is affected by remaining growth impacts in the last growing season and determines the tree and fruit quantity and quality for the preceding growing year. Two months' rest period in citrus is significant for flowers producing (particularly flower bud initiation) at about l0 °C. The fine soil texture results in better soil aeration, and prevents diseases including root-rot disease.

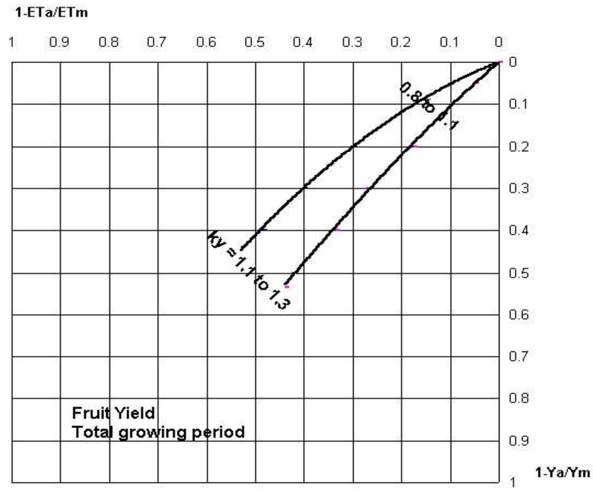

Figure 3.13. Seasonal development relationship between the relative yield reduction (1-Ya/Ym) against relative evapotranspiration shortfall condition (FAO Land and Water).

During the low N application at 100 kg ha^{-1}, the yields of orange (*C. sinensis*) led yields reveals low at 33 t ha^{-1} which are 25% less yield production, high N application at 300 kg ha^{-1} provides a high production yield at 43 t ha^{-1}., so the optimal water and fertilizer application must be provided to significantly maximize orange yield production by > 13% (Qin et al. 2016). The yield of citrus varies from tree-tree whereas for a single tree, yield varies from year-year. The mandarin provides 20-30 tons' ha^{-1} $year^{-1}$, lemons reveal 30-45 tons' ha^{-1} $year^{-1}$, grapefruit production ranges from 40-60 tons' ha^{-1}, while the orange production ranges from 25-40 tons' ha^{-1} $year^{-1}$. Results of the study conducted by Giwa et al. (2018) found that the orange peels are a significant resource of providing essential oils up to 4.40% (steam distillation), 3.47% (water distillation), and 2.536% (solvent extraction) under certain circumstances.

Irrigation water uptake

In general, citrus trees grow a single tap root with which lateral roots are developed and further the weakly developed root hairs are associated, known as the feeding roots. These roots search for nutrients and water simultaneously at the depth of about 1.20-2 m inside the soil. Experiencing the prolonged days of water stress conditions, the citrus tree roots evolve differently to the soil depth of 2-3 m in search of deep soil water and nutrients. Shahzad et al. (2020) shows that the *Candidatus liberibacter* trees had significantly downgraded levels of micronutrients including Mn, Zn, and Fe. Results showed that nutrient uptake potential per kilogram of root-tissues provided a higher value in *Candidatus liberibacter* trees and are highly efficient in nutrient uptake processes.

Irrigation scheduling

In citrus trees, they experience a high demand of soil water during the flowering and June/December drop period. During the 5-6 mm day^{-1} of ETm, the available soil water fraction (p) is considered as 0.4 where the soil water requirement of the crop is at peak. Citrus trees must be provided with better soil aeration conditions with the proper amount of irrigation water while over-irrigation could severely damage the trees by leaching of nutrients, inhibiting diseases, and affecting root development which could ultimately affect the total yield. A study recorded the seasonal maximum water applied, crop water consumed, and consumptive use efficiency (Ecu) under different irrigation regimes followed by the Jisemar and Azospirillum, whereas, several treatments showed maximum values related to water productivity and irrigation water productivity (Zaghloul et al. 2017).

Irrigation methods

Flood, basin, sprinkler (best for frost protection), drip and furrow irrigation methods are considered as the best method for citrus trees. Puglisi et al. (2019) conducted an experiment on orange, *C. sinensis* (L.), results of which shows that physiological response related to water stress conditions revealed non-significant variations in irrigation treatments, leaves ABA contents showed constant, while longer drying cycles enhanced the ABA contents in leaves. Morgan et al. (2010) conducted studies on orange irrigation methods and analyzed that the micro sprinkler system is most advantageous compared to the sprinkler system. Efficiency of the sprinkler systems are lower than the 80% in total. While micro irrigation methods are typically highly prioritized as these systems provide irrigation water directly to the crop root-zone where irrigation water losses are experienced to be at minimum scale, ET is lower which leads to efficient productivity (90% to 95%) of the water delivery system (Morgan 2010).

3.4.2. Olive (*O. europaea*)

Crop and climate

Olive, *O. europaea* originally came from the Middle East region. Production of the green and black table olives is estimated to be around 16 million tons and olive oil production is about 2.7 million tons. The 95 % out of the total production is estimated to produce in the Middle-East while other major producing countries are Italy and Spain (FAOSTAT 2001). Warm summers give a high oil content to the fruit. Under poor soil conditions, the crop provides acceptable yield production considering its deepness, aeration and waterlog free condition.

Olive fertilizer needs

Olive crop requirements for fertilizer are estimated to be 200-250 kg ha^{-1}, 55-70 kg ha^{-1} and 160-210 kg ha^{-1} for the N-P-K ratio. A study showed effects of two treatments such as full irrigation and half irrigation regimes as 75 and 50 % NPK, oil contents in fruits showed 100 % NPK, 75 % NPK, and 75 % NPK, while the highest chlorophyll contents was 75 % NPK and 75 % NPK (Sary and Elsokkary 2019). Miyasaka et al. (2016) showed that the fruit weight yield of the olive ranges from 2.14-2.45 (2013-14), and 0.25-22.06 (2015) kg $tree^{-1}$.

Table 3.5. Olive soluble fertilizer taken up by the plant at a given region and climatological condition (FAO Land and Water).

Country resource	Plant Nutrient Requirements (Kg ha^{-1})		
	N	P_2O_5	K_2O
Available from earlier crops	8	2	14
Uptake by the Olive tree	78	19	98
Removed by the Olive tree	40	7	60

Ben-Gal et al. (2017) investigated five water salinity (ECi) levels in Olive plantations with 0.5-11.0 dS m^{-1} for a constant leaching fraction of 0.29 and five leaching levels with 0.05-0.44 water of 5.0 dS m^{-1} of ECi, whereas soil salinity decreased tree water consumption and tree size (above-ground biomass) by 40-60 % as it increased from 1.2 to around 3.5–4.0 dS m^{-1}. Trabelsi et al. (2019) showed that after re-watering, photosynthetic rate of rainfed treatment showed 55% irrigated with fresh water, irrigation with saline water (EC = 7.5 dS m^{-1}) increased photosynthetic processes by 55% and showed a lower value of fresh water by 23%. Olive tree crop production in an economic version is considered as 50 years (minimum) but with better management practices, perfect soil and water, and better weather conditions can take it for a longer time.

Table 3.6. Olive major crop coefficients significant for the crop production and yield growth parameters (FAO Land and Water).

Stages of development						**Plant date**	**Region(s)**
Crop characteristics	**Initial**	**Crop development**	**Mid-season**	**Late**	**Total**		
Stage length (in days)	30	90	60	90	270	March	Meditteranean
Depletion coefficient (p)	-	-	-	-	0.65		
Root depth (Zr) (m)	-	-	-	-	1.7		
Crop coefficient (kc)	0.65	>>	0.70	0.70	-		
Yield response factor (ky)	0.2						

The coefficients described in Table 3.6 shows about 40-60% crop biomass and estimates Kc at immature stage. The monthly Kc for Olive crop having 60% biomass: 0.45, 0.50 and 0.65 from January to December. These coefficients are invoked by the Kc_{ini}=0.65, Kc_{mid}=0.45 and Kc_{end}=0.65 with length of the stage = 30, 90, 60 and 90 days, respectively. Lengths of days of crop developmental stages provide general perspective, but may affect sometimes, depending on the climate and cropping conditions and crop variety. Tests are primarily conducted on the required parameters of the local field.

Crop water needs

The water requirement of olive oil is comparative less than the other crops as 400-600 mm (even 200 mm in some regions) amount of water is required. Olive oil when received 600-800 mm provides high yields in better environmental conditions with the kc ranges from 0.4-0.6. A study revealed that olive crop Water demands are likely to be enhanced up to 3%, while ETc is to decrease up to 5.5%-21.7% while net irrigation olive crop requirements are to increase up to 29.5-103.4 mm (Knezevic et al. 2017). Ahumada-Orellana et al. (2017) showed that the treatments T2, T3, and T4 provided good yield in 37, 51, and 72 days with experiencing water stress regimes and showed 75–83, 62–76, and 56–70% of applied water, respectively, while irrigation cut-off strategy could save 20% of the irrigation water.

Water availability and yield production

Moderate amount of water is needed for maximum yield production to harden the fruit stone until the harvest stage. With high water availability, the fruit yields production quantity, quality, size, and flesh-pit ratio maximize, but reveals short leaves and twigs, and dense foliage. In case of table olive production, a precise amount of irrigation water is required after the crop development (flowering) stage. Olives for oil products are harvested with the timeline ranges from mid-December to March. Commercial olive yield production following a good irrigation practice produces 50 100 kg tree^{-1} fruit, with the oil production from fruit ranges from 20-25%. Ribeiro et al. (2017) showed the RPI de-trended data for the Olive crop-yield forecasting as the minimum forecasting precision with the level of 63%, while observed and modeled average deviation production minimized and showed 14% providing the maximum deviation length of 33%. For predicting *O. europaea* (L.) yield production, the most accurate forecast model RMSE showed the lowest observed data as 452.80 and 398.75 (Achmakh et al. 2020).

Irrigation water uptake

The olive tree with its growth in 3 or 4 years develops the fascicle rooting system, which can grow up to 12 m in length (lateral roots) in search of nutrients and water. Under 5-6 mm day^{-1} of maximum evapotranspiration (ETm), the crop to soil Irrigation water uptake ratio reduces up to 60-70 % of the total available soil water. Autovino et al. (2018) measured soil water contents in olive orchards at different distances with 0.04-0.09 cm^3 cm^{-3} RMSE values of the root system. A study examined that root hydraulic resistance constitutes 81% of the resistance during moderate irrigation regimes, which increases to > 95% during moderate irrigation stress. The decline of root hydraulic processes occurs in high irrigation stress regimes in olive plants (Rodriguez-Dominguez et al. 2019.

Irrigation scheduling

Different irrigation methods are applied (depending on region to region) but drip and surface irrigation are considered best for high yields. In winter, the irrigation is also required after 500 mm of rain during and at the end of the stone hardening stage. Under minor rains in winter, irrigation is required prior to flowering stage, during yield formation stage, and during stone hardening stage. For olive oil products, irrigation must be prohibited during the maturity stage which will maximize the oil content in the fruit. Capra et al. (2018) revealed that sustained deficit irrigation and regulated deficit irrigation saves 36%-54% (average) of energy and water while high-plant-density fields with sustained deficit irrigation reveals minimum water and energy needs.

3.4.3. Soybean (*G. max*)

Crop and climate

Soybean, *G. max* crop is considered to produce a significant amount of oil and good quality protein worldwide. Soybean world production shows 176.6 million tons of beans following the supplemental irrigation methods (FAOSTAT 2001). The crop growth is affected by the temperature which is > 35 °C and < 18 °C in any given climate. Total growing period of the soybean crop ranges from 100-130 days (in some regions more). The row-row distance in soybean crop ranges from 0.4-

0.6 m and 30-40 seeds metre^{-1} in a row is practiced. The suitable soil pH value for the soybean growth stages from 6-6.5 pH value for a commercial bean production.

Soybean fertilizer needs

The N-P-K fertilizer requirement doses of soybean crop ranges from 10-20 kg ha^{-1}, 15-30 kg ha^{-1}, and 25-60 kg ha^{-1}, respectively. The soybean crop is also able to fix the Atmospheric-N for the best commercial bean yield production. Study of the Shen et al. (2018) revealed that greater N fertilizer rates cannot enhance crop yield in maize-soybean intercropping, but showed a significant C-fixation rates in maize monoculture by providing Nitrogen at the rates of 240 kg ha^{-1}.

Kruger et al. (2020) showed that intercropping of soybean (*G. max* L.) and corn (*Zea mays* L.) at sandy-loam-soils has a significant declined rate in yield production. The study revealed 50% (EC50) yield cut at sandy-loam-soil showing the value of 7.04 for the salinity tolerance indices (STI) in soybean crop and the value of 9.68 in corn crop.

Table 3.7. Soybean major crop coefficients significant for the crop production and yield growth parameters (FAO Land and Water).

Stages of development						**Plant date**	**Region(s)**
Crop characteristics	**Initial**	**Crop development**	**Mid-season**	**Late**	**Total**		
Stage length (in days)	15	15	40	15	85	Dec	Tropics
	20	30/35	60	25	140	May	Central USA
	20	25	75	30	150	June	Japan
Depletion coefficient (p)	0.5	>>	0.6	0.9	0.5		
Root depth (Zr) (m)	0.3	>>	>>	1.0	-		
Crop coefficient (kc)	0.5	>>	1.15	0.5	-		
Yield response factor (ky)	0.2	0.8	-	1.0	0.85		

Crop water needs

Figure 3.14. Solar fertigation system working at the crop fields.

Soybean crop Water demands on a seasonal basis range from 450-700 mm (Depends on region–region, climate, soil and plant characteristics). The stage and length of the crop has diverse water requirements determined by crop coefficient (kc) values. However, kc of the soybean at initial stage is (0.3-0.4), development stage (0.7-0. 8), mid-season stage (1.0-1.15), late-season stage (0.7-0.8), while harvest is given as (0.4-0.5). Suryadi et al. (2018) showed that the seasonal amount of crop water requirement in soybean is 349.6 mm. Kumar et al. (2019) conducted a study by employing the FAO P–M model for computing the reference evapotranspiration (ETo). Crop data taken with lysimeter was evaluated with the help of remote sensed crop evapotranspiration (ETc) which provided the values of 0.44mm, 0.66mm and 25.15% viz. MBE, RMSE and MPE, respectively. While the soybean seasonal crop water requirement showed 304.40 mm and 349.50 mm using the remote sensing and lysimeter techniques, respectively.

Water availability and yield production

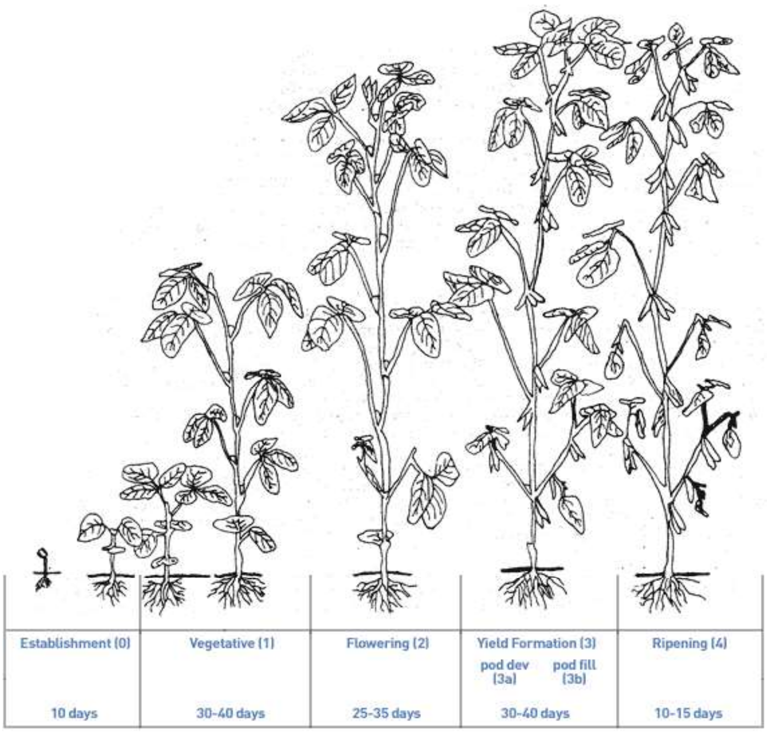

Figure 3.15. Different growth periods of soybean crop and their respective length in days (FAO Land and Water).

Growth development of the soybean crop is determined by the soil moisture availability at the root-zone which affects crop growth, yield formation quality and quantity, flowering and pod formation and/or droppings, and the respective delays in development stages. The adequate soil moisture level and perfect soil conditions constitutes ≤ 50% depletion level for the suitable pod fill up, yield formation, and high yield production.

The two development stages are critical and sensitive to water stress such as establishment period, and early yield formation which requires to provide adequate water supply during these periods. However, in conditions of water stress, the stages such as the vegetative stage, and near maturity (late-stage) could withhold the water scarcity conditions.

Crop irrigation regimes have shown an insignificant impact on protein and oil contents of the crop. In normal conditions, soybean crops yield ranges from 1.5-2.5 tons ha^{-1} seed with adequate irrigation regimes whereas, hybrid soybean yields provide 2.5-3.5-ton ha^{-1} seed. Antoneli et al. (2019) revealed a positive linear curve in soybean crop yield production ranging from 2.45-3.08 Mg ha^{-1} yr^{-}

^{1}, which was recorded for significant soil parameters including porosity and exchangeable cations content. Gavili et al. (2019) showed that by applying 0-75-ton cattle manure-derived biochar ha^{-1} under water-holding capacity reveals a high soybean crop grain yield. While 100-ton biochar ha^{-1} highly affects the yield production in a negative way, as biochar could positively be utilized for the high soybean yields in drought stress regimes. Ahmadi et al. (2017) showed the highest yield production of the soybean crop was revealed 1764.7 kg ha^{-1} while the lowest yield was revealed as 466.1 kg ha^{-1}.

Irrigation water uptake

The soybean crop is sensitive to water scarcity and availability which affects its root growth (> 1.5 m in length) which starts to highly develop during the flowering stage. The root-zone ranges from 0.6-1.3 m plays a significant role for the soil moisture uptake while this range of the root-zone provides 100 % water to the crop. The germination stage can withhold the water content level from 50-85 % of the available soil water while below or above this range could damage the crop.

Irrigation scheduling

In some regions, supplemental irrigation periods are also provided to the soybean crop to significantly maximize their yield production. Integration with the irrigation periods should be covered while irrigation at the early pod filling stage reveals a significant increase in pod and other yield production. Ahmadi et al. (2017) conducted a study to calculate the seasonal soybean crop water status index (CWSI) and revealed the values of 0.18, 0.37, 0.61 and 0.84 for four treatments. The study shows that a decline in per unit of irrigation water continuously rises the CWSI with the 0.15% rate. The study validated that the relationship of CWSI and grain yield production has a greater correlation of r= 0.98, whereas, the yield significantly decreases by maximizing the amount of CWSI. The study showed that the CWSI (0.18) governed the irrigation scheduling in the soybean field.

Irrigation methods

Soybean is generally grown provided irrigation with furrow irrigation method. For soybean crops grown with high value cover crops, the sprinkler irrigation method can also be practiced.

Potato (*S. tuberosum*)

Crop and climate

Potato, *S. tuberosum* originated from the south American high-altitude regions. *S. tuberosum* crops total yield production is about 308 million tons at the cultivated land of 19 million ha. (FAOSTAT 2001). The high yield from the *S. tuberosum* crop could be obtained at the temperatures ranging from 18-20 °C (slight changes in different regions) with the daytime length of about 15-17 hours. *S. tuberosum* varieties have the ability to cope with the different climatological conditions due to which they are grouped into early, medium, and late varieties with the differences in days ranging from 150-180 days, 120-150 days, and 90-120 days, respectively. *S. tuberosum* should be sowed at the depth of 5-10 cm with other crops including maize, beans and alfalfa in a rotation to preserve the natural soil efficiency at the soil pH value of 5-6.

Potato fertilizer needs

The fertilizer demands particularly, the N-P-K fertilizers for the *S. tuberosum* ranges from 80-120 kg ha^{-1}, 50-80 kg ha^{-1} and 125-160 kg ha^{-1}, respectively. Soratto et al. (2020) studied that the soils with lower potential of K-contents enhance the potato plants biomass regardless of the types of the management, whereas, soils with lower potential of K-contents may not significantly affect the plant dry matter content. Jahanzad et al. (2017) conducted tests and validated that the potato tuber yield production and nitrogen use efficiency are strongly relevant to the lowest (75 kg ha^{-1}) or highest (225 kg ha^{-1}) of N-fertilizer levels. The study further validated that the crop grown in no-cover-crop-plots required 225 kg ha^{-1} of nitrogen for the highest yield production (26.5 mg ha^{-1}). While the potato crop grown after winter pea or radish crop revealed the same high yields by using the 75 and 150 Kg ha^{-1} of nitrogen, respectively.

Table 3.8. Potato soluble fertilizer requirements at each day, at different development stages and their respected crop coefficients (FAO Land and Water).

Tomato growth stages	**Tomato soluble fertilizer requirements (kg ha^{-1} day^{-1})**			**Tomato soluble fertilizer requirements (kg ha^{-1} stage^{-1})**			**Tomato crop coefficient (kc)**
	N	**P_2O_5**	**K_2O**	**N**	**P_2O_5**	**K_2O**	
Planting stage	1	0	1	1	0	1	0.5
Vegetative stage	1.56	0.54	2.44	61	21	95	>>
Tuber initiation and bulking stage	3.15	1.08	4.85	126	43	194	1.15
Maturity stage	2.36	0.82	3.64	118	41	182	0.5

Islam et al. (2018) studied that the soil salinity content in raised soil-bed was shown lower while at the flat soil-bed, the soil salinity content was rather high. Results showed that the soil-beds which had lower soil salinity (raised soil-beds) revealed 13.04% greater tuber yield production than the other treatments. Studies of El-Wahed et al. (2020) showed that different levels of mulching and irrigation regimes highly affect the soil salinity as making the salt content to increase or decrease its content from its initial level.

Table 3.9. Potato major crop coefficients significant for the crop production and yield growth parameters (FAO Land and Water).

Stages of development						**Plant date**	**Region(s)**
Crop characteristics	**Initial**	**Crop development**	**Mid season**	**Late**	**Total**		
Stage length (in days)	25	30	30/45	30	115/130	Jan/Nov	(Semi) Arid climate
	25	30	45	30	130	May	Continental climate
	30	35	50	30	145	Apr	Europe
	45	30	70	20	165	Apr/May	Idaho
	30	35	50	25	140	Dec	Calf. desert
Depletion coefficient (p)	0.5	>>	0.6	0.9	0.5		
Root depth (Zr) (m)	0.3	>>	>>	1.0	-		
Crop coefficient (kc)	0.5	>>	1.15	0.5	-		
Yield response factor (ky)	0.2	0.8	-	1.0	0.85		

Crop water needs

The *S. tuberosum* crop water demands (ETm) in European regions ranges from 500 to 700 mm (slight changes for different regions). The crop coefficient (kc) of *S. tuberosum* at the initial stage is given as 0.4-0.5, the development stage shows 0.7-0.8, while the mid-season stage reveals 1.05-1.2. Whereas, the kc of *S. tuberosum* for the late-season stage ranges from 0.85-0.95, and at maturity it shows 0.7-0.75. Gebremariam et al. (2018) showed that the depth of irrigation application significantly affected the *S. tuberosum* crop yield production and WUE. Study showed the highest yield production was (25864 kg ha^{-1}) by applying 100% of ETc, while 70% of ETc revealed the crop yield production of 22639 kg ha^{-1}, which showed a non-significant trend against the 100% ETc. The Kc_{end} value for Potato crop is 0.40 with vine kill.

Water availability and yield production

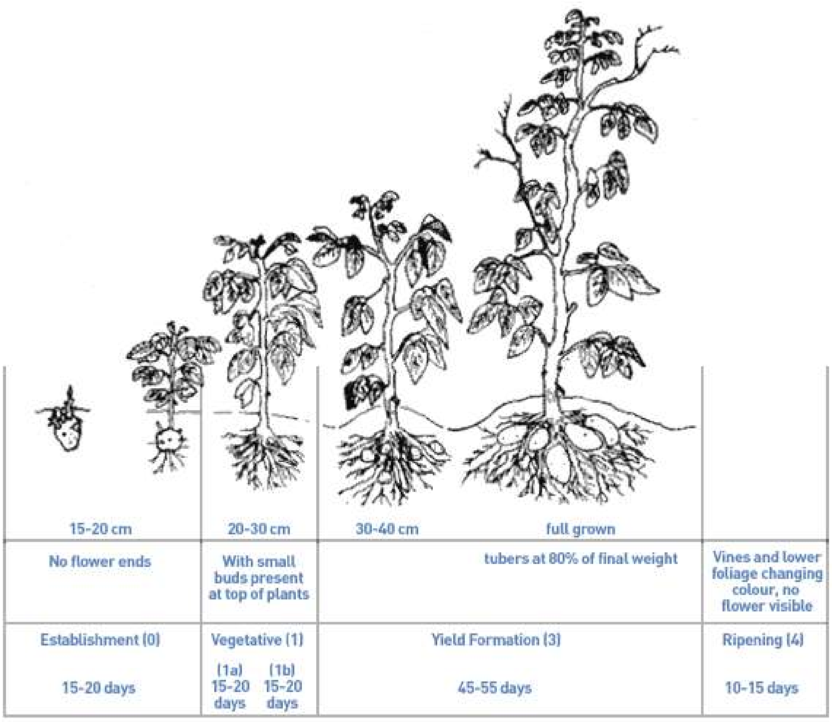

Figure 3.16. Different growth stages of the *S. tuberosum* crop (FAO Land and Water).

To harvest the optimized *S. tuberosum* crop yield production, the total available soil moisture in the root-zone must be in the range of 30-50 %. Varieties of the *S. tuberosum* have shown a diverse set of responses to soil moisture content at different stages, keeping the fact that high moisture content maximizes the crop yield production. While the stages such as stolonization, tuber initiation, and yield formation are highly sensitive to the soil moisture availability, ripening and early vegetative stages have shown rather less relatedness to the soil moisture availability.

Dry matter and stolonization content of the crop increases with moderate quantities of irrigation regimes during the ripening stage. The yield production of the *S. tuberosum* crop within the range of 25-35-ton ha^{-1} is considered as good (slighter difference from region-region in yield production). Winnicki et al. (2017) studied the European potato varieties which showed that the Adam cultivar is least significant for high yield production for its low starch, while the minimum unit costs for producing starch appeared during the assessment of the Sleza European potato cultivar.

Water uptake

The soil water depletion effect was shown at about 25 % under the evaporative conditions (ETm) of 5-6 mm day^{-1} at a specific climate. A significant amount of soil moisture uptake is performed by the upper 0.3 m rooting system, while the remaining water uptake is performed by the rest of 0.4-0.6 m rooting system.

Irrigation scheduling

The stages of stolonization, tuber initiation, and yield formation should be taken care of. While the early vegetative, and ripening stages could be kept in the non-irrigation regimes.

Irrigation methods

For high yield production of the *S. tuberosum*, the furrow and sprinkler irrigation methods are recommended with frequent irrigation techniques. A significant increasing trend in yield production is revealed following the mechanized sprinkler irrigation method in conditions to address the daily ET_O demands of the crop.

Cabbage (*B. oleracea* var. capitata)

Crop and climate

Cabbage, *B. oleracea var. capitata* originates from the south and western European regions, while total production is 55 million tons at 2.6 million ha. of land (FAOSTAT 2001). For good yield production, the growing period of the crop ranges from 120-140 days under a certain temperature ranging from 24 °C max and 10 °C min while temperature outside this range may harm the plant and yield production. Leaves of the crop smaller < 3 cm survive longer duration of low temperature but leaves from 5-7 cm leads to a poor-quality yield production. The heavier loam soils with improved drainage and aeration are perfect for the growth and production.

Cabbage fertilizer needs

The *B. oleracea* var. capitate fertilizer requirements particularly N-P-K are ranges from 100-150 kg ha^{-1}, 50-65 kg ha^{-1}, and 100-130 kg ha^{-1}, respectively. Sikura et al. (2020) conducted a study on cabbage and used slow-release nutrient fertilizers which revealed a greater commercial yield production by using the nitrogen fertilizers with 108 kg ha^{-1} rate. Chuan et al. (2019) concluded field trials with the nutrients N-P-K application rate of 112.98, 35.03, and 213.15 kg ha^{-1}, respectively. While the yield production efficiency of the nutrient fertilizers showed 26.6, 13.9, and 16.6 t ha^{-1} respectively, whereas, the agronomic efficiencies were 114.3, 108.5, and 89.4 kg kg^{-1} with average.

Table 3.10. Cabbage crop average rates of soluble fertilizer requirement (kg ha^{-1}) (FAO Land and Water).

N	**P_2O_5**	**K_2O**
120-160	50-100	180-200

Table 3.11. Cabbage crop Fertigation requirement with different rates at different development stages (kg ha^{-1}) (FAO Land and Water).

Development Stages	**Nutrients required (kg ha^{-1} day^{-1})**		
	N	**P_2O_5**	**K_2O**
Planting (45 days)	1.013	1.14	1.08
46-70 days after harvest	3.33	1.36	3.73
71- harvest days	0.74	0.32	0.84

Sahin et al. (2018) concluded that the increased levels of soil salinity negatively affect the plant growth particularly, dry mass, roots, and shoots. The study further observed that sucrose and proline levels provoke plant development within the certain levels of soil salinity. While in regimes of the increased soil salinity, a negative impact on plant's transpiration rate (Tr), intercellular CO2 content (Ci), net photosynthetic activity (An), stomatal conductance (gs), leaf relative water content (LRWC), and chlorophyll content (SPAD) appears.

Figure 3.17. Full-grown Cabbage, *B. oleracea var. capitate* with green leaves and white flowers (FAO Land and Water).

Table 3.12. *B. oleracea var. capitata* major crop coefficients significant for the crop production and yield growth parameters (FAO Land and Water).

Stages of development						**Plant date**	**Region(s)**
Crop characteristics	**Initial**	**Crop development**	**Mid season**	**Late**	**Total**		
Stage length (in days)	40	60	50	15	165	September	California desert
Depletion coefficient (p)	0.4	>>	0.4	0.4	-		
Root depth (Zr) (m)	0.25	>>	>>	0.5	-		
Crop coefficient (kc)	0.7	>>	1.05	0.95	-		
Yield response factor (ky)	0.2	-	0.45	0.6	0.95		

Crop water needs

B. oleracea var. capitata seasonal water demands ranges from 380-500 mm (slightly different in various regions). The *B. oleracea var. capitata* crop coefficient (kc) initiates at the initial growth period which is (0.4-0.5), at crop development period kc is (0.7-0.8), at mid-season stage kc is (0.95-1.1), at late season stage kc is (0.9-1.0), while at harvest the kc is (0.8-0.95). Beshir (2017) reveals that the cabbage water requirement ranges from 2.57-5.81 mm day^{-1} with two irrigation regimes in 7 days is considered an adequate and better irrigation for the good yield production of cabbage.

Water availability and yield production

The vegetative stage of the *B. oleracea var. capitata* is sensitive to the water deficit conditions while the yield is affected by water stress regimes. For regions where water scarcity is available, the growing area should be extended while partial meeting the crop water demands may provide a significant yield production.

The yields range from 25-85-ton ha^{-1} in well controlled conditions. Verma et al. (2017) showed that the maximum biological yields, heads, and fresh biomass (92.9, 55.1, and 37.9 t ha^{-1}) were revealed the highest yield production with the application of 100% RDF, humic acid, and *Pseudomonas fluorescens*.

Water uptake

B. oleracea var. capitata has shallow roots in which the roots ranging from 0.4-0.5 m provide a significant larger amount of soil moisture to the plant. Under 5-6 mm day^{-1} of ETm conditions, the water uptake rate is minimized during the soil depletion reached to 35 % or when the depletion factor p reaches to 0.35. Wang et al. (2019) showed that serials of the root uptake within hydroponic condition are as: fenbuconazole, then ivermectin, then thiamethoxam, and then spirotetramat. The highly demanded was the thiamethoxam and were easily taken to the plant while ivermectin, fenbuconazole, and spirotetramat were shown accumulated inside the roots.

Irrigation scheduling

As *B. oleracea var. capitata* is a green plant, so the irrigation water regime ranges from 3-12 days (slightly different in various regions). Under irrigation water deficit conditions, the end of the growing period of the crop should be provided multiple times.

Irrigation methods

The sub-soil irrigation method is considered best for high yield production while trickle, sprinkler, and furrow irrigation methods have also shown good results. Shinde et al. (2020) showed in their field trials that the highest cabbage yield production was provided in the micro-sprinkler irrigation method with 37 t ha^{-1}, and 35.5 t ha^{-1} of production with 1 and 0.9 ETc, respectively. The maximum WUE revealed was 114 kg ha^{-1} mm^{-1} following the drip irrigation method and 0.9 ETc content was found, while micro-sprinkler irrigation method provided 7.30% higher yield production than the drip irrigation.

Onion (*A. cepa*)

Crop and climate

Onion, *A. cepa* originated western and eastern Asia while the total yield production of the *A. cepa* is 46.7 million tons (app.) at the 2.7 million ha. of cultivated land (FAOSTAT 2001). *A. cepa* makes bulbs in the first development season while flowers are created in the second growth season. The warm and dry weather is suitable for high yield of qualitative production under the temperature ranges between 15-20 °C, while length of the growth stages ranges from 130-175 days (slightly different in various regions). Transplantation from nursery to fields of the *A. cepa* is done after 30-35 days with the field spacing of 0.3-0.5 × 0.05-0.1 m. The soil pH ranging from 6-7 pH value suits best for production.

Onion fertilizer needs

A. cepa nutrient fertilizer such as N-P-K requirements ranges from 60-100 kg ha^{-1}, 25-45 kg ha^{-1}, and 45-80 kg ha^{-1}, respectively. Mubarak et al. (2018) showed that the nitrogen nutrient fertilizer content (60 kg ha^{-1}) revealed the maximum total bulb yield production was 19.1 t ha^{-1}, bulb dry matter was 2.97 t ha^{-1}, and WUE was 1.9 kg m^{-3} in the full irrigation conditions. El-Hamdi et al. (2016) revealed that the commercial yield of fresh and dry masses of *A. cepa* was increased with the N-P-K application following the rate of 50, 50, and 100 kg ha^{-1}. Plant height and WUE was also increased by this rate of application in the certain region.

Table 3.13. A. cepa crop soluble fertilizer requirements at each base dressing (FAO Land and Water).

Fertilizer Nutrient Requirements (Kg ha^{-1})		
N	**P_2O_5**	**K_2O**
37	120	90

Table 3.14. A. cepa crop fertigation requirement after several weeks of transplanting (FAO Land and Water).

Weeks after transplanting plant	**Fertigation requirements**		
	N	**P_2O_5**	**K_2O**
2-6	14	-	-
8-12	6.5	-	23

Yohannes et al. (2020) evaluated different yield responses at various irrigation regimes in non-saline canal water (with EC ranges 0.41 – 0.78 dS m^{-1}) and slightly saline seepage water (with EC ranges 0.82-2.19 dS m^{-1}) on *A. cepa* crops. The total yield production variations in between various treatments showed a non-significant trend, whereas, some treatment was responsible for significantly reducing the yield production, dry mass and bulbs in saline water.

Figure 3.18. Onion plant passing through its yield formation stage in the field (FAO Land and Water).

Table 3.15. Onion major crop coefficients significant for the crop production and yield growth parameters (FAO Land and Water).

Stages of development						**Plant date**	**Region(s)**
Crop characteristics	**Initial**	**Crop development**	**Mid-season**	**Late**	**Total**		
Stage length (in days)	15	25	70	40	150	April	Mediterranean
	20	35	110	45	210	Oct/Jan	Arid regions and California
Depletion coefficient (p)	-	-	-	-	0.3		
Root depth (Zr) (m)	-	-	-	-	0.6		
Crop coefficient (kc)	0.7	>>	1.05	0.75	-		
Yield response factor (ky)	0.45	-	0.8	0.3	1.1		

Crop water needs

Water demands of *A. cepa* is in between 350-550 mm water. While the crop coefficient (kc) at the initial growing period is 0.4-0.6, crop development period is 0.7-0.8, mid-season period is 0.95-1. 1, late-season period is 0.85-0.9, and harvest is 0. 75-0.85. Enchalew et al. (2016) showed that plant height has showed a non-significant trend to water deficit irrigation regime, whereas, total bulb dry mass, marketable yield production (15,690 kg ha^{-1}), bulb diameter, and leaf numbers revealed a significant difference for water deficit irrigation condition. Abdelkhalik et al. (2019a) revealed that the deficit irrigation conditions decreased the commercial yield production of *A. cepa.* A moderate dry mass yield production was achieved with regulated deficit irrigation technique (75% potential) of the irrigation water requirements leading to reduce down the dry mass yield production by 4%, and increase up the irrigation water use efficiency by 9%.

Water availability and crop yield production

A. cepa has shown sensitive responses to water stress regimes particularly the yield formation stage of bulb development. An adequate percent of soil water depletion such as < 25 % should be maintained. The bulb enlargement could be practiced with high amounts of soil moisture. While the growth stages range from 100-140 days (slightly different in various regions) and including establishment stage (30-35 days), vegetation stage (25-30 days), yield formation stage (50-80 days), and ripening stage (25-30 days). Adequate irrigation regimes and quantity should be provided at the yield formation stage to gain larger bulbs and their maximum weight, while at ripening and vegetative stages, the water supply could be saved as required.

A good crop yield production ranges from 35-45-ton ha^{-1}, while the WUE for harvested yield (Ey) of crop is 8-10 kg m^{-3} under the condition of 85-90 % moisture. Ali et al. (2018) showed that the organic poultry manure application in *A. cepa* crop significantly increased the total yield by 33.9 tones ha^{-1}, bulb weight by 93.4 g, average bulb diameter by 10.2 cm, and the plant height by 79.3 cm, while the varieties "Parachinar local" significantly enhanced total yield by 27.4 tones ha^{-1}, bulb weight by 88.1 g, average bulb diameter by 7.7 cm, and plant height by 69.5 cm.

Water uptake

A. cepa constitutes a shallow rooting system while 100 % of the water and nutrient uptake to plant occurs from the initial 0.3-0.5 root system. The evapotranspiration demand rate in between 5-6 mm day^{-1} is considered suitable for achieving higher production, whereas, in condition of 25% of depletion of the total available water, the water uptake rates decline.

Irrigation scheduling

A. cepa requires less but frequent irrigation regimes within 2-4 days until 25 % of available water is depleted in its root-zone. *A. cepa* is highly fragile to diseases especially in over-irrigation conditions where the bulbs got diseases within days including white rot, and mildew. The basin and furrow irrigation methods are commonly practiced for the *A. cepa* cropping systems.

Pepper (*C. annuum*)

Crop and climate

Pepper, *Capsicum annum* has originated from the tropics of America and the total world production is 19 million tons grown at 1.5 million ha. of land (FAOSTAT 2001). The best suitable temperature and rainfall conditions for *C. annum* growth ranges from 18-27 °C, and 600-1250 mm per growing season. The perfect growth soil ranges from 5.5-7.0 pH value of soil. Optimum temperature for seed germination ranges from 20-24 °C which are transplanted after 25-35 days in the field. The total growing period ranges from 120-150 days (slightly different in various other regions). Mature and red peppers should be harvested at 1-2-week intervals for 3 consecutive months.

Pepper fertilizer needs

C. annum soluble nutrient fertilizer requirements including N-P-K are 100-170 kg ha^{-1}, 25-50 kg ha^{-1}, and 550-100 kg ha^{-1}, respectively. Youzhe et al. (2016) revealed that the optimal N nutrients fertilizer close to the range of 225 kg hm^{-2} had a significant trend on commercial yield. The N fertilizer application at the rate of 194.00 and 192.69 kg hm^{-2} showed a moderate significant marketable yield and WUE at the given location. Coolong et al. (2019) showed that the total marketable yield production was highest such as 910 boxes acre with the application of Ca nutrient fertilizers at the rate of 196 kg ha^{-1} N, while the commercial yield production within the range of 600-800 boxes ha^{-1} with the application of supplemental Ca at the rate of 224 kg ha^{-1} N.

Table 3.16. Pepper (*C. annuum*) crop soluble fertilizer requirement at each day and development stages (FAO Land and Water).

Pepper growth stages	**Requirements per day (kg ha^{-1} day^{-1})**			**Requirements per stage (kg ha^{-1} $stage^{-1}$)**		
	N	**P_2O_5**	**K_2O**	**N**	**P_2O_5**	**K_2O**
Planting stage	1	0	1	1	0	1
1st growth stage	0.66	0.24	1.07	119	7	31
Development stage	2.65	0.95	43	106	38	172
Maturity stage	1.98	0.72	3.23	119	43	194

Rameshwaran et al. (2016) conducted an experiment on the soil salinity effects on total yield production of the *C. annuum* which showed that higher levels of soil salinity provoked more salt accumulation within root-zone of the crop, whereas higher levels of saline irrigation water enhanced the size of the root-zone layers. The study further revealed that higher soil salinity levels significantly reduced vegetative as well as the dry biomass yield production of the pepper.

Table 3.17. Pepper major crop coefficients significant for the crop production and yield growth parameters (FAO Land and Water).

Stages of development						**Plant date**	**Region(s)**
Crop characteristics	**Initial**	**Crop development**	**Mid season**	**Late**	**Total**		
Stage length (in days)	25-30	35	40	20	125	Apr/Jun	Europe/Mediterranean
	30	40	110	30	210	Oct	Arid climates
Depletion coefficient (p)	0.2	>>	0.3	0.5	0.3		
Root depth (Zr) (m)	0.25	>>	-	0.8	-		
Crop coefficient (kc)	0.6	>>	1.05	0.9	-		
Yield response factor (ky)	-	-	-	-	1.1		

Crop water needs

The crop water requirement (ETm) of the *C. annum* ranges from 600-900 (1250 mm in few regions). While the crop coefficient (kc) at the transplanting stage is 0.4, at full cover kc is 0.95-1. 1, and at maturity stage kc is 0.8-0.9. Arya et al. (2017) showed that the observed maximum and minimum evapotranspiration (ETo) of *C. annuum* in the month of December was recorded as 4.59- and 1.72-mm day^{-1}, respectively. The kc was kept constant at each growth stage of the crop as described by Allen et al. (1998). While the total water requirement of the *A. annuum* was considered as 380 mm for the whole crop growing season.

Water availability and crop yield production

A moderate moist soil is required for the high yields of *C. annuum*. Soil moisture reduction at flowering (or before) significantly damages the yield production and the quantity of fruits, while the soil water depletion in the root zone should be < 25 %. Water stress regimes at maturity stage pushes the fruits to shrivel, malformed, and ultimately affects quality of the fruit pungent.

The commercial yield production of the *C. annuum* ranges from 10-25-ton ha^{-1}. While the WUE for harvested yield (Ey) in average is 90 % within the range of 1.5-3.0 kg m^{-3}. Bione et al.

(2020) revealed that the pepper marketable yield production was shown as 2.87 kg $plant^{-1}$ using the hydroponic systems, in correlation with the 46.1 Mg ha^{-1} grown at the area of 0.62 m^2 $plant^{-1}$ cultivated land. David (2018) concluded that *C. annuum* plants showed a significantly delayed competence with 78%-89% reductions in total yield by weight, 59%-93% reduced development in plants, and 58% reduced marketable yield. While the *C. annuum* treated to Scarface provided 32% higher commercial yield, 15%-18% heavier fruits (weight), and 9-12% more market benefits than others treated with ‘Karisma’.

Water uptake

Pepper shows a revolutionary two types of rooting systems; tap rooting system and lateral rooting system which are divided into transplanting and field growth periods, respectively. The rooting system ranges between the first 0.5-1.0 m provides a significant amount of soil moisture and nutrient fertilizers (Sarafi et al. 2018). Ropokis et al. (2019) presented that different grafting regimes in *C. annuum* can significantly affect the yield production and nutrient uptake, and may not only depend on the genotype rootstock but also on the combination of the rootstock or scion.

Irrigation scheduling

For high yield production of *C. annuum*, the soil water depletion should be maintained in between the range of 30-40 % of the total available soil water in the root zone. This moisture level could be kept normal by 4-7 days’ irrigation frequencies (depends on the region, soil and climate).

Irrigation methods

For high yielding capacity of *C. annuum*, the sprinkler and drip irrigation methods are considered suitable while for good yield production, the irrigation methods of surface and furrow are considered to apply.

Tomato (*L. esculentum*)

Crop and climate

Tomato, *L. esculentum* is the highly demanded crop after potato crop. At 3.7 million ha. land production of tomato vegetable crops appears to around 100 million tons (FAOSTAT 2001). The suitable mean daily temperature (day time) for growth is 18-25 ºC, while above 25 ºC minimizes the vegetative production, and fruit growth in a significant quantity. Well drained soil conditions with 5-7 pH value prohibits fruit rotting, different crop and fruit diseases, bacterial wilt, and pest attack. To avoid diseases, tomatoes should be grown with the cowpea, cabbage, and maize crops in rotation. Tomatoes are a little sensitive to salinity stress in soil especially the germination and early growth stage. Soil salinity when followed by drought conditions, leads to affect photosynthesis and impacting crop's cross-tolerance factors (Gururani et al. 2015; Murchie et al. 2010).

Table 3.18. Tomato major crop coefficients significant for the crop production and yield growth parameters (FAO Land and Water).

Stages of development						**Plant date**	**Region(s)**
Crop characteristics	**Initial**	**Crop development**	**Mid-season**	**Late**	**Total**		
Stage length (in days)	30	40	40	25	135	Jan	Arid regions
	35	40	50	30	155	Apr/May	California
	25	40	60	30	155	Jan	California desert
	35	45	70	30	180	Oct/Nov	Arid regions
	30	40	45	30	145	Apr/May	Mediterranean regions
Depletion coefficient (p)	0.3	>>	0.4	0.5	0.3		
Root depth (Zr) (m)	0.25	>>	-	1.0	-		
Crop coefficient (kc)	0.6	>>	1.15	0.7-0.9	-		
Yield response factor (ky)	0.4	1.1	0.8	0.4	1.05		

Tomato fertilizer needs

Tomato requires N in a high amount during its vegetative stage and utilizes about 150–300 kg ha^{-1} of nitrogen (Dumas 1990). Nitrogen requirements of tomatoes are revealed maximum (100-400 kg ha^{-1}) after the vegetative stage (Warner et al. 2004; Geisseler et al. 2020) reveals that N-application rates do not increase or decrease tomato crop yield as total N in fruits were not affected by fertilizer with 60.6% in 2017, and 67.2% in 2018. Tomato fertilizer requirements are rather high than the other crops (Zucco et al. 2015).

Barzee et al. (2019) studied the ultra-filtered dairy manure digestate biofertilizer (DMP). Study revealed the maximum tomato crop yield with 7.13-ton ha^{-1}, followed by food waste digestate bio fertilizer (FWC) with 6.26 tons' ha^{-1}, and Nitrogen-N fertilizers with 5.98-ton ha^{-1}. Khan et al. (2019) showed an increase in the fruit mineral traits and size diameter, crop water content, nutrient availability, fresh and dry biomass, chlorophyll availability, flowering quantity and size, and fruit quality and quantity.

Table 3.19. Tomato crop soluble fertilizer requirement at each development stage and their respected crop coefficient (FAO Land and Water).

Tomato growth stages	Requirements per day (kg ha^{-1} day^{-1})			Requirements per stage (kg ha^{-1} $stage^{-1}$)			Tomato crop coefficient (kc)
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	
Initial stage	1	0	1	1	0	1	0.6
Crop-development stage	1.17	0.27	1.86	17	4	27	>>
Mid-season stage	0.6	0.2	0.9	6	2	9	1.15
Late stage	1.2	0.3	1.9	24	6	38	0.9

Geisseler et al. (2020) applied N with 28 kg ha^{-1} to the tomato crop plants. The N, P_2O_5, K2O, and Zn fertilizers revealed an increase in the crops yield, with 130 mg ha^{-1} in 2017, and 140 mg ha^{-1} in 2018.

Crop water needs

Tomato crop water requirement in field conditions ranges from 400-600 mm (for tomatoes of growth cycle 90-120 days). The water requirement of a crop is highly dependent on the reference evapotranspiration (ETo), and crop factor (kc) given in mm/period which reveals differences in every growth stage of the crop. In Italy, Rinaldi et al. (2007) revealed frequent application rates have a high impact on its water use efficiency, while the seasonal irrigation water application rates (600 and 800 mm) showed a low water use efficiency.

In southern Italy, tomato vegetable crops produce 200 fresh and 120 t ha^{-1} dry total biomass followed by an average irrigation requirement of 400 mm (generally depends on climate). Seasonal irrigation rates (600-800 mm) prevent drainage and N-leaching in tomato crops. Ewaid et al. (2019) revealed values of ETo and effective rainfall with 2.18-10.5 mm day^{-1} and 0.0-23.1 mm, respectively. The crop Water demands for tomatoes revealed (1180) mm dec^{-1} while the seasonal and net irrigation for tomatoes showed 203.3 mm and 142.3 mm, respectively (Katerji et al. 2010).

Water availability and yield production

In tomato, fruits are ripened while the flowers are growing and maturing while in other varieties three periods to mature flowers can be related with the three harvest periods. The continuous irrigation application for tomato crops develops fruit juice, color, shape, and size but acidity and dry mass content will negatively be impacted. Tomato yield related to the range in between 45-65 tons' ha^{-1} fruit (fresh quality) is considered as the best yield. While the WUE for fresh tomato yield (harvested) is considered as 10-12 kg m^{-3}. The tomato crop water application depends on the end product such as if used for salad, requires less amount of irrigation water or if used in paste, requires a high amount of irrigation water. Liu et al. (2019) showed that irrigation water deficit conditions significantly impacted all the growth stages with low yield. The study examined 75% of ETc revealed to be a balanced irrigation application for crop yield quality and quantity, crops lycopene concentration, and a higher level of total carotenoids level (Takacs et al. 2020). Lovelli et al. (2017) claims the total yield of tomato vegetable crop minimizes by 37% (yearly rate) during 50% of the irrigation and crop evapotranspiration (ETc), while the maximum crop yield was examined under the 100% irrigation and ETc conditions. A study revealed that the irrigation depth above 80% (ETc) enhances the tomato fruit production, leaf area index (LAI), and crop growth rate (CGR) (Monte et al. 2013).

Table 3.20. Tomato crop growth stages and their length until the first harvest stage (FAO Land and Water).

Stages	Development stages	Stage length (days)
0	Pre-vegetative	25-35
1	Vegetative	20-25
2	Flowering	20-30
3	Yielding	20-30
4	Maturity	15-20
Total		100-140 days

The tomato crop is moderately sensitive to water deficit experience in field conditions, and highly sensitive during flowering and yield formation stages, affecting the flowers to lose and ultimately drop. The water stress condition during the vegetative stage of the crop shows a significant root growth development.

Irrigation water uptake

Tomato crops have a moderate deep rooting system with 1. 5 m deep roots (during maturity stage) into the soil. The 80% crop water requirement is fulfilled with the 0.5-0.7 m rooting system, while the remaining Irrigation water uptake is being provided by the 0.7-1.5 m crop rooting systems. In a special condition of 5-6 mm day^{-1} maximum evapotranspiration (ETm), the total available soil water impacts the crop Irrigation water uptake if it shows the availability of less than 40%.

Romero-Aranda et al. (2001) showed that Irrigation water uptake of tomato vegetable crops is minimized when electrical conductivity is increased. Studies by Schwarz et al. (1998) shows that at 9 dS m^{-1} (EC), Irrigation water uptake of the plants was minimized to 60 %. De Swaef et al. (2012) claims that a decrease in hydraulic conductivity lowers-down the water-uptake potential of the tomato crop plants in a significant amount.

Irrigation scheduling

For tomato crop, heavy irrigation application and water deficit conditions at any stage could seriously damage the crop growth and fruit production. High care is required in irrigation during the flowering stage, any stress factor or over irrigation could damage flowers, inhibit longer vegetative stage, and later on maturity delay.

The perfect environmental conditions for salad tomato crop are regular irrigations, lit-day, and well-distributed with the soil-depletion below 40% ($p < 0.4$). Which are the suitable conditions for tomato growth and promotes maximum production yield and quality. While for the tomato paste crop, a high irrigation quantity is required at the pre-flowering stage.

A study carried out by Liu et al. (2013) showed that the irrigation quantity (total), seasonal ETc, and crop yield (Y) revealed 185.1-365.8 mm, 249.1-388.0 mm and 99.6–151.8 t ha^{-1}, respectively and enhanced crop yield, fruit number, total soluble solid (TSS) content and its yield, fruit firmness, WUE, and irrigation WUE, but no effect on fruit weight (mean), fruit diameter, and length of stages. Said et al. (2013) revealed that the WUE with a higher value (7.33 kg m^{-3}), intelligent control system (ICT) revealed a rather lower value under (5.33 kg m^{-3}).

Irrigation methods

For tomato crops, the surface (in furrows) and drip irrigation methods are considered as highly successful irrigation methods. In sprinkler irrigation methods, there is a high chance of fungal and bacterial canker diseases attack, fruits may experience fruit rotting, leaf burn and other crop growth problems may persist. Studies of Malash et al. (2012) confirms that drip irrigation method in tomato crops enhances crops growth, yield and WUE, in regards to furrow irrigation method. Malash et al. (2012) utilized 3 dS m^{-1} of saline water and revealed the yield parallel to the non-saline treatments during the drip-irrigation method.

Alomran et al. (2012) applied subsurface drip irrigation method at 2 L h^{-1} flow rate, and revealed that fresh application of saline water with 6 L h^{-1} flow rate minimized the high cost of water desalination and saline water effects. A study validated that partial root-zone irrigation method minimizes the leaf transpiration rate, and fruits organic acid content (by 5.3%), but maximizes the leaf and yield WUE, root-zone activity, fruit yield production, soluble sugar in fruits (by 4.5%), and Vitamin-C content (by 12.6%) (Yang et al. 2012).

Watermelon (*C. lanatus*)

Crop and climate

Watermelon, known also as *C. lanatus,* originated in the tropics and subtropics of the African region while the total crop production is 77.5 million tons (app.) cultivated at 3.1 million ha. land (FAOSTAT 2001). The suitable growth temperature is hot and dry and the crop development provokes significant good yield in the temperatures ranges from 22-30 °C, while the temperature must not be higher or lower than the range such as 18-35 °C. The fruits constitute the 11 % sugar content are considered as better yield production, while the crop completes its growth stages in 80-110 days (slightly different in other regions). The good production of *C. lanatus* can be provided with 5.8-7.2 pH value of the soil.

Watermelon fertilizer needs

The nutrient fertilizer requirements for high yield production are 80-100 kg ha^{-1} N, 25-60 kg ha^{-1} P, and 35-80 kg ha K recommended rates. Kang et al. (2020) revealed a linear development ranging from 60–70% in *C. lanatus* total yield production. The study utilized a balanced number of nutrient fertilizers (N, P, and K) for the production of 1000 kg yield. The study applied nitrogen 2.11 kg, phosphorus 0.27 kg, and potassium 2.69 kg for the crops, while the internal efficiencies (IE) recorded N-P-K valued for the 475, 3682, and 372 kg fruit per kg of nutrient fertilizers, respectively. Du et al. (2019) recorded that the *C. lanatus* yield production showed an increasing trend ranging from 27.4%, 30.2% and 31.6%. The nutrient fertilizers including N-application increased the yield ranging from 26.3%, 39.8% and 47.4%, P-application improved the yield by 48.3%, 49.3%, and 55.9%, while the K-application increased the yield production of *C. lanatus* by 35.8%, 41.6% and 51.9%.

Pinheiro et al. (2019) recorded that the watermelon growth production is affected by the soil salinity stress. The treatments in better soil showed an increasing trend in week 4 and 7 at field conditions rather plants experienced soil salinity stress with 20, 25, 30 and 35% of exchangeable sodium ions. The study showed that watermelon is sensitive to the soil salinity stress.

Table 3.21. Watermelon major crop coefficients significant for the crop production and yield growth parameters (FAO Land and Water).

Stages of development						**Plant date**	**Region(s)**
Crop characteristics	**Initial**	**Crop development**	**Mid-season**	**Late**	**Total**		
Stage length (in days)	20	30	30	30	110	Apr	Italian region
	10	20	20	30	80	Mar-Aug	East desert regions
Depletion coefficient (p)	-	-	-	-	0.4		
Root depth (Zr) (m)	-	-	-	-	0.8		
Crop coefficient (kc)	0.4	>>	1.0	0.75	-		
Yield response factor (ky)	0.45	0.8	0.8	0.3	1.1		

Crop water needs

If the evaporative demands of the *C. lanatus* are completed, the irrigation intervals may be kept within the range of 6-8 days (depends on region to region). The crop coefficients (kc) at different growth stages varies and starts from the initial growth stage. At initial stage, kc is 0.4-0.5, kc at development stage is 0.7-0.8, kc at mid-season stage is 0.95-1.05, kc at late-season stage is 0.8-0.9, while at harvest kc is 0.65-0.75. Abdelkhalik et al. (2019b) applied the irrigation water requirements (IWR) ranging from 100, 75 and 50% and a treatment experienced a deficit irrigation with 75% IWR, while few experienced 50% IWR in different growth stages. The study concluded that a reduction in yield biomass, total commercial yield, fruit weight and size, and HI shoed a non-significant increasing trend. Pejic et al. (2016) revealed that watermelon yield production under irrigated regimes (398 mm) recorded 37.28 t ha^{-1} with a highly significant trend, while the treatments in a water stress regime (117 mm) showed 9.98 t ha^{-1}.

Water availability and yield production

In conditions of the soil depletion where 50-70 % of available soil water has depleted, the irrigation should be provided accordingly. The *C. lanatus* has the capacity to provide moderate yield such as 15-ton ha^{-1} in dry and arid regions. The total growth stages range from 80-110 days. *C. lanatus* provides 4-fruits plant (depends on the pruning season^{-1}), while the harvest stage depends on the fruit number plant^{-1}. Late flowering or early vegetative stages are sensitive to water deficit and if experienced water deficit, a significant loss of yield may occur, while better if water deficit conditions are provided during the ripening stage which provide highest fruit quality.

The marketable yield of the *C. lanatus* from 25-35-ton ha^{-1} is considered as good yield production while the WUE for harvested yield (Ey) for 90 % moisture ranges from 5-8 kg m^{-3}. Fuentes et al. (2018) recorded that the drip-plastic and -bare irrigation methods provided 46 and 60% reduced water saving capacity, while the furrow irrigation recorded better. Whereas, the maximum WUE was recorded at the drip irrigation method by recording plastic mulch at about 27.6 kg m, and bare soil recorded 23.1 kg m. Pereira et al. (2017) assessed different loss variables relating to the physiological aspects and bacterial, fungal, and insect attack, and discovered models to increase crop yield. While major variables responsible for watermelon yield reduction are abnormal fruits, flower abortion, and crop death attacked by *Didymella bryoniae*. The study shows that the crop yield reduction is maximum in humid and rainy season.

Water uptake

The roots of *C. lanatus* constitute an extensive system with the 1.5-2 m in depth. The first 1.0-1.5 m of the rooting system provides the major soil moisture and nutrient fertilizers present in the root-zone. Under the conditions of 5-6 mm day^{-1} (moderate) evapotranspiration, *C. lanatus* depletes the root-zone available soil moisture to 40-50 %.

Irrigation scheduling

The frequent irrigation regimes such as 7-10 days must be provided for high yielding *C. lanatus*. Under water deficit and water saving strategy conditions, irrigation schedules should be created for growing stage, late vegetative stage, flowering stage, and yield development stage (preferred water deficit condition to maximize sugary-material, and avoid fibrous and less juicy content) while 50% soil water depletion should be kept as maximum.

Irrigation methods

The irrigation stress regimes may not affect the number of fruits but their quality including fruit size, bad shape, and lighter weights. The furrow and drip irrigation methods are considered as the high yield predicting methods, while flood or spate irrigation methods following the 250-350 mm irrigation water application have shown some significant positive results.

3.5. Data collection (2019–2021)

Crop growth is considered as a sensitive factor to environmental factors. They affect crop yield, production, and cropping system with huge spatial differences. The data was collected for all the test fields with the years 2019–2021. Various models were tested for the environmental parameters data collection such as temperature, humidity, wind, rainfall, and Ultraviolet (UV) radiation.

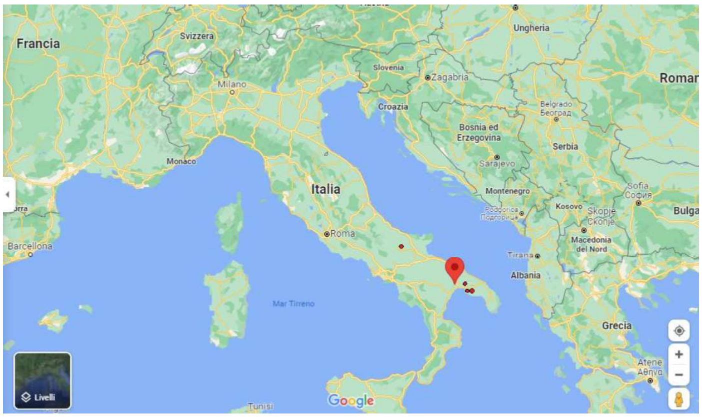

Figure 3.19. Test fields and weather stations in the Italian region using MeteoInMolise and iLMeteo resource (Google Maps).

3.5.1. MeteoInMolise and iLMeteo Resources

Figure 3.20. Official MeteoInMolise of the Molise region.

The MeteoInMolise was initiated in 2015 which was used to collect real-time data for Molise region. The official site is focused on to become the region's meteorological research resource and grow as a network of WMO established meteorological platform and aims to develop strategic collaborations with other networks.

Figure 3.21. Official iLMeteo resource of the Molise region.

iLMeteo is a technological association working since 2000. The team from those years have created novel empirical and mathematical techniques for weather forecast analysis. The resource is considered for the provision of facilities and communication of meteorological forecasts and is considered to be the premier Italian weather resource (Audiweb 2019).

For particular days when the rainfall data is not available, MeteoInMolise and iLMeteo official resource provided a whole set of observations from 2019–2021. The MeteoInMolise and iLMeteo official resources provided the data which were found with issues due to which a corrected factor was implemented. So, the recorded data (2019–2020) was corrected using the tested methods. The four models were utilized and created data for these missing months so that it could fill the available gap for those months. The correction factor was performed using these models based on these procedures. The first procedure was to compare the acquired MeteoInMolise and iLMeteo data with the first model on daily basis and estimate the results of these two datasets. The second procedure is to compare each acquired dataset with the average value of the second model (then third, and fourth). The relationship of MeteoInMolise and iLMeteo and four model data was measured using both the aforementioned procedures on weekly basis. For every 7-days timeline, the greatest relationship of both of these methods were examined while the gaps were filled to analyze the dataset for quality results.

Temperature data was collected on day-to-day minimum, maximum and average temperature using the official resources to estimate the crop evapotranspiration and phenological growth. Humidity data was measured from 08:00 to 20:00 (depending on the summer and winter seasons) and calculated the daily humidity average value. For wind data collection, corrected factor was performed (Allen et al. 1998) so that the boundary layer inconsistency and the vapor pressure buoyancy remain consistent. Rainfall data was collected using the MeteoInMolise, iLMeteo and the system whereas high variations were revealed between the total rainfall values of the dataset which were updated using the correction factor. Ultraviolet (UV) radiation data was acquired using the regular incident of sunshine hours depending on the cloud cover. The collected environmental data was processed and recognized for any errors and was updated with the correction factor (Table 3.22).

Table 3.22. Corrected datasets for weather forecast factors using the MeteoInMolise, and iLMeteo Weather Forecast resources (FAO Land and Water).

Parameters	**Maximum**	**Minimum**	**Measurement**
Maximum Temperature (T_{max})	40	10	°C
Minimum Temperature (T_{min})	30	0	°C
Average Temperature (T_{ave})	20	5	°C
Relative Humidity (RH)	80	40	%
UV-Radiation	30	10	MJ m^{-2}
Air speed	15	0	Km h^{-1}
Rainfall	5	0	mm day^{-1}

The collected data was a large set of formulations which was processed using mathematical and empirical methods. This method includes the recognition and updation of the datasets by validating the quality control check for the corrected figures (Table 3.22). The corrected figures were mapped using the annual parametric average of the local region. It consists of data sharing channel for logical monitoring of the data and minimize the differences. The updated data was later verified to guarantee the range without any strict overlay. The validation also includes verifying the factors for consistency trend along with other factors. Such as the consideration in maximum temperature should be kept as above than the minimum temperature at the given field. After the successful data correction process, the data was installed into the web–based desktop platform and was further analyzed.

Daily Temperature

The daily temperature data was acquired for maximum, minimum and average daily temperatures in each field. The data was collected from the official resources while the daily average temperature was measured using the average of maximum and minimum (Doorenbos et al. 1977):

$$T_{avg} = \frac{(T_{max} + T_{min})}{2} \qquad 3.1$$

The continuous temperature measurements were recorded. Data validation was conducted by determining different issues using the data comparison and correlation methods. The data comparison method consists of analyzing the collected data by estimating them with the other data. Each estimated data was compared with the temperature recordings of a different time on the same day. In this way, the greatest correlation resulted to reveal. The second procedure is the correlation examination of data recording to complete and data recording on the preceding days and comparing them with other trials. The analysis, based on comparison, resulted in developing relationships of temperature recordings for each time the measurement was conducted on daily basis.

The calculation was based on the daily average temperature as recordings were collected from 08:00 to 20:00 on daily basis. The accurate calculation of the temperature data was acquired as the collection method was based on a high number of representative measurements. As complete observations of the temperature datasets were available, the average temperature was precisely measured. The second option of measuring the daily average temperature was to measure it from the maximum and minimum temperature data with the help of the equation 3.1. The empirical method provides correlation analysis on the collected temperatures using official Italian resources and the system collected recordings. While the highest correlation in measuring the maximum and minimum temperature values were found to have few issues which were addressed.

The corrected analysis developed a set of logical datasets based on the minimum temperature values for all the test fields. Even in conditions of the north, south, west and east regions provided diverse set of rainfall data, the minimum temperature data got a huge impact by this pattern which is monitored in all the test fields. At Campobasso (Lat. 41.55947, Lon. 14.66737) station, the system acquisition data recorded linear trend than the official resources. The system acquisition is considered highly recognized upon a slighter influence from environmental direct contact. Upon analysis of the other test fields, a slightly different temperature recordings were acquired due to plain areas, while the system was supposed to perform the correctness check at few datasets. Minimum temperature data was observed in Late-January at one test field while the others collected them while the data was added for the first one using the correctness factor method.

The four models were not considered to acquire the best temperature data especially the maximum temperature. The datasets collected from the humid test fields of Apulia region (Montemesola, and Castellaneta) were determined in an accurate shape. The temperature data at Marina di Ginosa were constantly corrected for the value up to 8 °C. The south and east temperature patterns were recorded for maximum temperature using the official resources such as MeteoInMolise and iLMeteo. Except Campobasso, the test fields recorded highest temperature data from May-July while the highest corrected data was recorded for the rainy months in December and January. The datasets were constantly overestimated for the Campobasso east zone while underestimated for the west zone.

The annual temperature analysis provided by the solar fertigation system for all the test fields appear parallel to the average annual correlation $R^2 = 0.58$ for minimum temperature, while for the maximum temperature, $R^2 = 0.51$. The rainy season correlation showed a poor trend. General features of south European region show that the diurnal temperature hours (in summer) are lower than the temperature difference on yearly basis. The study shows accurate prediction of the diurnal temperature hours (Equation 3.10), a method is provided for accurate estimation of the incoming UV-Radiation using the Hargreaves–Samani empirical method as;

$$ET = 0.0023 \times (T_{ave} + 17.8) \times (T_{max} - T_{min})^{0.5} \times Ra \quad 3.2$$

where 0.0023, and 17.8 are considered as constants in the H–S empirical method. T_{ave} is the average measured temperature, T_{max} is the maximum measured temperature, and T_{min} is the minimum measured temperature. While, Ra is the extraterrestrial radiation received at the surface of the earth.

Validated measurements were given for the Campobasso-N test field while its magnitude for the diurnal period was recorded low in winter/rainy season. At Campobasso-S, the data related to the diurnal period was corrected for up to 8 °C where it needed. The average temperature data was tended to forecast the plant phenological growth, and evapotranspiration potential. However, the recorded data of the system needed to be corrected by underestimating the average temperature hours for the winter/rainy months for all the test fields.

The system data was considered as to provide the annual temperature datasets; however, issues related to cloud cover were found, which were not accurately measured in particular fields, and later corrected using the comparison method. These issues were also relevant for the rainy/winter seasons that showed a high margin in tendency due to which the correlations of the solar fertigation system and the official resources were evaluated for 7-day timeline.

Daily relative humidity

The daily relative humidity (RH) data was collected with the help of the official resources. The humidity at different zones of the field was presented and analyzed by the solar fertigation web–based desktop platform. The real-time atmospheric pressure (ea) was also acquired using the resource and compared with the empirical method of Bolton (1980):

$$e_a = c_{ea} \times \frac{RH}{100} \times 0.6108 \exp \frac{(17.27\ T_{av})}{T_{av} + 237.3} \qquad 3.3$$

The variable c_{ea} in the equation 3.2 shows the corrected factors to avoid bias as this method is highly preferred due to the availability of the e_a average data. MeteoInMolise official resource further provided the calculations on bias parameters. This vapor pressure value was compared with the MeteoInMolise value (using the weekly estimation), the c_{ea} value revealed as 0.75 for all the tested fields. The particular temperature trend based on long-term rising-minimum was implemented due to the ability of the air to preserve high moisture at night and reduced condensation will occur. The daily RH values are measured by many researchers using Equation 3.2 in an alternative order with different time-line. The set hypothesis is based on the Bolton (1980) analysis that support the flat graph values.

The measured data for the parameters c_{ea}, as revealed, 0.75 underestimated the RH values, due to which was corrected to an exact figure of 1 (Houérou 2009). The RH data from 2019 to 2020 was recorded higher than in preceding year. One significant factor known as saturated vapor pressure (SVP) is the amount of water vapor needed to saturate the particular part of air at a specific time of the day. SVP is represented as e^s_a and is measured using the equation 3.3 with the corrected c_{ea} factor of 1 and RH as 100. The equation 3.3 is considered as a non-linear empirical approach based on underestimating the SVP. In an alternative solution, the SVP is measured using the equation 3.2 by using the minimum and maximum temperature values (Allen et al. 1998):

$$e^s_a = c_{ea}\,\frac{0.6108\exp\left(\frac{17.27T_{max}}{100}\right) + 0.6108\exp\left(\frac{17.27T_{min}}{T_{av} + 237.3}\right)}{2} \qquad 3.4$$

Though SVP is considered as a dependent factor of temperature, its variation provides a significant difference. An assessment was performed for the SVP validation using the mathematical and empirical approaches of MeteoInMolise and iLMeteo official resources as mentioned in equation 3.3 to underestimate the 12 hours SVP and overestimate 24 hours SVP values. Both of the factors resulted in a diverse set of values such as for 12 hours which revealed c_{ea} as 0.95, while for 12 hours the c_{ea} revealed as 0.82. For this reason, VPD is used for the determination of the evapotranspiration and the crop phenological stages. As mentioned below, equation 3.4 determines the difference of the vapor pressure deficit and SVP which is follows as:

$$VPD = e^s_a - e_a \qquad 3.5$$

Daily wind

The daily wind data supports the accuracy of the evapotranspiration which is estimated at 2 m height from the soil surface. Corrections can be applied for the height which is different from 2m above the ground. The wind data in the trials was recorded from 08:00 to 20:00 while the 24-hour data was not collected which was analyzed using the estimation method from regular monitoring. During the wind data collection, the wind speed during few hours of the day was monitored to be less, which was estimated as an average of the monitored data from 08:00 to 20:00. It was further noted that in few days the average data goes beyond the 15 km ha^{-1} which was later corrected using the comparison method and corrected figures were put into the data. However, the wind speed at larger crop canopies is weaker which were corrected for a realistic analysis.

Acquisition of the real-time average wind speed data is highly complex due to which the MeteoInMolise data from 2019 to 2021 were analyzed and compared with other values available in the literature (Thevs et al. 2021). During the data collection by the system, the wind data was recorded to be consistent while the iLMeteo datasets recorded higher values than the other. The comparison between the system data and the iLMeteo data showed a gap that results in higher and lower values and is still needed to find out if it appeared due to environmental parameters or a different technology. Upon validation, the iLMeteo data was compared and inserted a corrected factor which revealed a similar pattern with Karthe (2018).

During the summer months (May-Jul), wind speed was recorded to be minimum in all the test fields. The solar fertigation system developed the particular trends which consisted of corrected factors in different test fields. The factors such as wind speed data acquisition is a technical process due to regional specific and anemometer system particularities and their calculation methods. The solar fertigation wind speed data recorded a non-linear trend which needed to implement high level of correction factors followed by an annual correlation of R^2 (0.09).

The mean wind speed data recorded shows that the wind speed has increased in years from 2019 to 2021 by 0.50 %, though the increasing trend was previously predicted in the solar fertigation web–based desktop platform and the analyzed data acquired from the official resources. This might be due to the reason of air pressure variations during these years. As the wind blows in a horizontal direction from high pressure zone to low pressure zone. The wind speed is estimated by the gradient of atmospheric pressure difference between these two pressure zones. The higher the air pressure variation, the faster the wind speed (Wu et al. 2018).

Daily rainfall

The daily rainfall data was collected on daily basis using the official Italian web–based resources. Each of the list consists of total daily rainfall for particular hours and corrected factors were adjusted for number of hours, if missing. The days during the test were divided into six 4-hour period based on iLMeteo official site. Some of the periods measured no rainfall while others recorded numerous measurements. For accurate rainfall data analysis, the data were adjusted in a sequence. The adjustment included analysis of the 4-hour period to correct any dataset that needs to be adjusted. Analysis was based on: a) number of daily rainfall hours if multiplied with 3; b) datasets based on more than 24 hours' time period; c) high amount of rainfall > 25 mm in months which is not supposed to be; and d) half of the data acquired in 4-hour period is able to compare with another data. The data were updated if two of the above parameters meet; in this sense, 11 datasets were updated accordingly.

Further updates were performed in unnecessary data in the form of short periods, which appeared during long term rainfall data collection. The short-term data were overwritten with the long–term data. In 200 datasets of short-term data, it was noted that the short-term data is larger in number and shows a non-continuous trend. After completing this analysis, further data was still found to be available in a large amount for those days when rainfall were not present with short- and long-term datasets.

Long-term rainfall data was acquired from 2019 to 2021 for all the test fields with the help of MeteoInMolise. The data collected from these official resources were analyzed for any corrected factors which revealed that MeteoInMolise consists of multiple datasets with similar readings while iLMeteo contained just a single reading. This shows that the reading collected was over-written at the first one. There is a less chance that few rainfall events would provide the similar rainfall data, the second recorded reading was marked as zero. Many readings, such as 220 were affected. This happens more in the starting months of winter season where the rainy months are approaching and previous records were preserved in the system while new lists are made for new months.

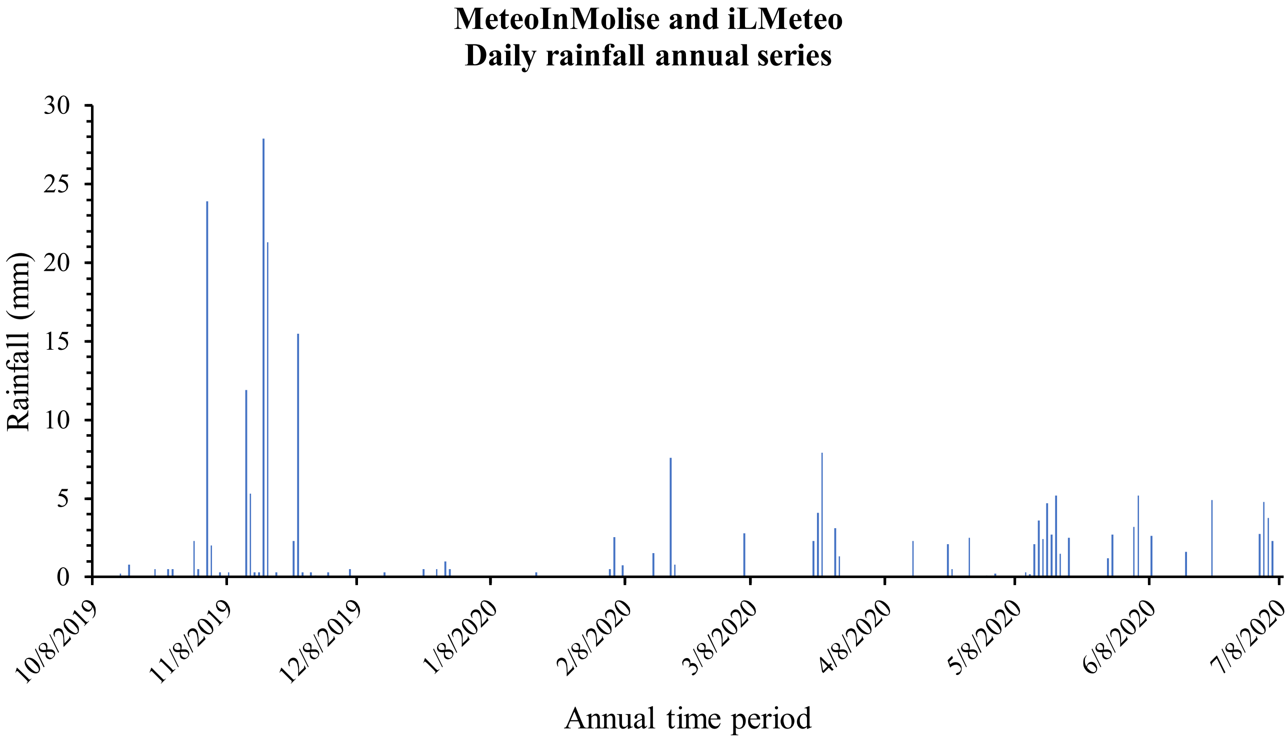

Figure 3.22. Daily rainfall annual series for the MeteoInMolise and iLMeteo official resources. Every value in the dataset is considered as an annual average of all the fields in Italy.

Data is analyzed with high rainfall record from December to March and minimum from April to August. At the minimum rainfall months, the corrected value for each day is estimated as zero mm. Other days such as 40 periods, showed no rainfall data for seven consistent days. The validation process was initiated to assess the data collected using these two resources for magnitude and distribution of rainfall. The yearly rainfall was compared from the years 2019 to 2021, the rainfall events of all the test fields using iLMeteo official resource was analyzed based on comparison method with the MeteoInMolise official resource and adjust on daily basis for the proximity values of the rainfall. The maximum value was noted for every field on annual basis. In 3 from total 5 groups, the nearest corrected value in the MeteoInMolise resource was set to put forward. For other situations, MeteoInMolise dataset was checked and adjusted as mentioned before. The adjustment was conducted only if values fall into the estimated range from 10 to 50%. Those values fall into the given ratio shows a strong correlation for the collected two datasets, while other values with low ratio dropped off. The rainfall measurement datasets were acquired with similar gauge or unit in all the test fields. It was extremely taken care of not to make any mistake during the rainfall data acquisition and analysis stage due to the complex correction methodology of the large datasets.

The correction procedures of the rainfall data acquisition and analysis shows low accuracy of data collection of the websites. MeteoInMolise shows minimum issues and a validation of continuous rainfall results with a repetition in the linear trend which is considered to be highly accurate. The same process for data validation at different fields recorded 100 more similar datasets collected through the MeteoInMolise resource. It results in suggesting that the MeteoInMolise resource is considered as highly accurate for crop management. The MeteoInMolise will also be analyzed after 2021 research with days of empty data cells; the Figure 3.22 shows that rainfall events occurred mostly prior to the 2020, through which it could be concluded that the estimation methods in this timeline have developed using empirical models and systematic technologies.

The acquisition of rainfall data shows a variable trend in temporal and spatial aspects. Few test fields are located on mountainous while others are located in plain regions. In mountainous region (Campobasso), the rainfall events happen on particular zones as showed by four models to implement the corrected factor due to which the measurements were recorded in a non-linear trend for their intensity, frequency and size. For plain region test fields, the data recorded significant linear trend with low adjustments for all the test fields from the years 2019-2021. The data in plain regions was compared on the basis of mean rate of rainfall events, while the solar fertigation system measured 2.1 mm in each occurrence in comparison to the official resource 2.9 mm per occurrence.

The solar fertigation system data is based on a late acquisition of the rainfall occurrence in most of the test fields. Rainfall events initiate with short frequencies, and keep on occurring with an irregular, and reduced interval rather than the measured. The rainfall rate measured by the solar fertigation system, particularly in heavy rainfall conditions in Campobasso, was recorded very low at south test fields which are the plain areas. The data recorded in the months from Apr-Sep showed a logical trend where minor adjustments were performed. For the initial few months of the data recordings, the solar fertigation data tend to be adjusted only for heavy rainfall or winter months. Considering the above presented studies, it is concluded that the solar fertigation rainfall data need to be adjusted in a minor quantity, however, in an overall analysis, the developed solar fertigation system provided significant datasets which could analyze the required factors in an optimum way.

Daily ultraviolet radiation

The daily ultraviolet (UV) radiation data acquisition recorded minor changes in the tests. The four models adjusted the UV-radiation data for all the tests during the rainy months, which caused variations due to the extremely low temperatures, dense clouds, and high fog even at day time. The data acquired during the summer months showed a linear trend, however, the solar fertigation system needed to adjust few datasets related to the UV-radiation at few test fields. Four datasets were noted which showed a constant linear trend although the MeteoInMolise official resource recorded to be slighter higher in few regions. The data analyzed shows that the mean annual UV-radiation maximized by 0.30 % from the years 2019-2021, that is considered as an 8 % increase in the sunshine hours. This increase in the years from 2019-2021 shows that the climate change effects are impacting the region and its relevant factors. It is clear from the study that the data related to an increase in the solar radiation is collected in an accurate method. The increase of the UV-radiation is highly recorded at the Marina di Ginosa from all the test fields. The increase does not record any significant effect on cropping systems and growth parameters.

The UV-radiation data was acquired from 2019 to 2021 using the MeteoInMolise and iLMeteo official resource. Official resource such as photovoltaic software (Simulation and Design of Solar Systems) provide PV-solar radiation data from about 1960 till today. The MeteoInMolise resource provided the UV-radiation data for the day time hours and previous historic data, following similar gauge or unit with the rainfall factor. Doorenbos et al. (1977) showed the accurate cloud and sunshine data with consistent values (Table 3.23).

Table 3.23. Corrected adjustment factors for UV-Sunshine Radiation and cloud cover parameters based on Doorenbos et al. (1977).

Cloud Factor	Corrected Factor 0	Corrected Factor 1	Corrected Factor 2	Corrected Factor 3	Corrected Factor 4
N / n	0.90	0.80	0.70	0.60	0.50

N is considered as the number of daylight hours, while n is considered as the number of sunshine hours.

The UV-Radiation data was not collected from August 2020 till April 2021. In this timeline, the number of hours for the radiation was determined from available cloud cover hours. The available cloud cover hours were analyzed with the help of the okta gauge (min 0 and max 8). The data availability quality was dependent on the collection method. The available cloud cover hours were collected by resulting an average value for all the previous observations in hours.

For this reason, various techniques were used for the analysis of the UV-Radiation in hours from the available cloud cover hours on daily basis. The Doorenbos et al. (1977) recommended in the FAO manual that shows estimation from the available cloud cover hours with its particular corrected factors (Table 3.23).

The data related to the a_s and b_s constants were determined from multiple studies (Table 3.24). UV-Radiation and sunshine hours' data acquisition were conducted using the MeteoInMolise official weather forecast resource for the years 2019–2021. The empirical equation 3.9 was updated and extracted the relevant data related to the R_{dsw}/R_a to analyze n/N for the specified number of days. For analyzing this data, regression analysis of two constants such as a_s and b_s was performed with respective values 0.24 and 0.29, and R^2 value was 0.52. The data shows that the highest values of the constants ($a_s + b_s$) reveal as 0.69.

Table 3.24. Empirical techniques for estimating the incident UV-Radiation (R_{dsw}) from the data of extraterrestrial radiation (R_a). The models were presented by ASHRAE, Machler et al. Parishwad et al. and Nijegorodov.

Method	Factors			References
	a_s	b_s	$a_s + b_s$	

ASHRAE Model (Empirical method)	0.142	0.058	0.134	ASHRAE (1985)
Machler and Iqbal's Model (Technical method)	0.141	0.103	0.137	Machler et al. (1967)
Parishwad's Model (Empirical method)	0.036	0.242	0.495	Parishwad et al. (1997)
Nijegorodov's Model (Systematic method)	0.177	0.114	0.162	Nijegorodov (1996)

ASHRAE method

The ASHRAE algorithm model deliver an easy technique that is widely accepted for results execution in architectural and engineering fields (ASHRAE 1985).

Machler and Iqbal's method

Machler et al. (1967) analyzed the diffused irradiation data on hourly basis from UV-Radiation received at the horizontal surface. The study suggests that analyzing the solar elevation ranges higher than the 40º is technical study. The study contributed in providing further values for the constant factors such as a_s, b_s and $a_s + b_s$, that is considered as an advancement in the UV-Radiation study.

Parishwad's method

Parishwad et al. (1997) analyzed the constant factors of the ASHRAE method with the help of the statistical empirical approach to determine the UV-Radiation in six different regions in India.

Nijegorodov's method

Nijegorodov further studied constant factors of ASHRAE method with the help of the computer systems and analyzed day-to-day UV-Radiation based on collected UV-Radiation on hourly basis in three different regions such as Zimbabwe, Namibia, and Botswana (Nijegorodov 1996).

3.5.2. Reference evapotranspiration (ETo)

The empirical approaches presented in this thesis compute the reference evapotranspiration (ETo) using different methods and environmental factors. The standards presented by the Food and

Agriculture Organization (FAO) of the United Nations suggests that the use of the empirical method depends on the user needs, data availability, data size, and accurateness of the empirical method. The data could be adjusted, if needed, in a particular region using the available environmental factors, local meteorological stations, and previous analysis, while few methods could also provide analysis with missing data.

Calculating the ETo is a technical process due to data availability and system measurements. A general and practical method for estimating the ETo is the pan evaporation method. The Class-A pan with a standard size is filled with the particular amount of water on daily basis. The calculation is conducted on 24-hours period about the quantity of water loss and required amount of water. In Class-A pan, it is noted that the type of pan should be the one suggested by the FAO56 Manual. The rate of evaporation depends on several features such as the pan type, environmental factors of the pan (dense or sparse vegetation), and the heat transfer flux between the pan, soil surface, and environment (Jones 1992). Dodds et al. (2005) in his study shows various flaws in the Pan evaporation method such as 1) the architecture of the pan is completely different from the crop architecture due to which the evaporation in freely available evaporative pan and that of crop is different, as in crop, it depends on the stage and type of crop, and 2) the pan calculation of the ETo is strictly dependent on the exact position, environmental conditions of the pan in field, and user's expertise due to which differences in local evaporative demand and sites does not provide accurate results in most cases.

Studies have used other manual methods for estimating the ETo by using another technology which is known as the lysimeter. The method is composed of a set of instruments which are installed inside the soil surface at the particular position with having a soil slab of soil above the soil surface. The weight of soil slab diversifies with the passage of time due to water addition. The soil surface is provided with the irrigation water on daily basis while there is a proper system available that calculate the loss of water from the received water. The instrument is composed of a large homogeneous field, while various scales are placed over it that decrease any impact from external environment. Lysimeters provide good results but are very expensive and cannot be afforded by all.

Different models have been developed for ETo assessment but several requires the daily meteorological data delivered by weather stations. This thesis assessed two temperature–based models, such as Hargreaves–Samani (H–S) (Hargreaves and Samani 1985), and Blaney–Criddle (B–C) (Blaney and Criddle 1950). These models are considered as the most suitable and flexible models for the estimation of the ETo in all the environmental conditions.

Hargreaves–Samani (H–S) model

The FAO irrigation and drainage paper 56 Crop evapotranspiration is a perfect manual to evaluate the evapotranspiration models. In the cases of daily T-min and T-max, humidity, wind speed and sunshine hours are available for the given test site. The Hargreaves–Samani (H–S) method is employed using T-max and T-min data to calculate the ETo, which is very common among researchers. This approach was further developed by Allen et al. (1998) to perfectly blend the FAO-56 crop evapotranspiration manual. The H–S being an empirical approach includes the empirical coefficients. While it can be used with other standard data-sets, as several authors (Allen et al. 1998) suggested to calibrate H–S in regards to FAO-56 at different trial fields with comparable climatic regions.

However, it is not mandatory using these climatic variables as this approach (H–S and B–C) is being thought of as an easy implemented and simple model to calculate the ETo. The H–S equation performs better in semi-arid and arid regions as their climatic conditions are perfectly integrated together (López-Urrea et al. 2006), while is not suitable for humid climates (Wang et al. 2014. The empirical method for Hargreaves–Samani model is presented as below:

$$ET = 0.0023 \times (T_{ave} + 17.8) \times (T_{max} - T_{min})^{0.5} \times \text{UV-Radiation} \quad 3.6$$

whereas

0.0023 and 17.8 are constants in the H–S empirical method

T_{ave} is the average measured temperature

T_{max} is the maximum measured temperature

T_{min} is the minimum measured temperature, and

UV-Radiation is the total measured sunshine radiation received at the surface of the earth.

Blaney–Criddle (B–C) model

The Blaney–Criddle (B–C) model (Blaney and Criddle 1950) is used for estimating the reference crop evapotranspiration by using a simplistic approach in the case when sufficient meteorological data is available. However, the Penman–Monteith equation is mostly preferred in many scenarios. The B–C model is used to calculate the one month or more when air-temperature datasets of the test-fields are available (Allen et al. 1986).

$$ETo = p \times (0.457 \times T_{mean} + 8.128) \quad 3.7$$

whereas

ETo is the reference evapotranspiration (mm day^{-1})

T_{mean} is the mean daily temperature (°C) given as $T_{mean} = (T_{max} + T_{min})/2$

p is the mean daily percentage of annual daytime hours.

The p-value determines the mean daily percentage of annual daytime hours for different latitudes at different regions of the world. The p-value is acquired by the table (Brouwer and Heibloem 1986) as given below.

Table 3.25. Mean daily percentage (p) value of annual daytime hours for different latitudes (Blaney and Criddle 1950).

Latitude	**North**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
	South	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**
60°	-	.15	.20	.26	.32	.38	.41	.40	.34	.28	.22	.17	.13
55°	-	.17	.21	.26	.32	.36	.39	.38	.33	.28	.23	.18	.16
50°	-	.19	.23	.27	.31	.34	.36	.35	.32	.28	.24	.20	.18
45°	-	.20	.23	.27	.30	.34	.35	.34	.32	.28	.24	.21	.20
40°	-	.22	.24	.27	.30	.32	.34	.33	.31	.28	.25	.22	.21
35°	-	.23	.25	.27	.29	.31	.32	.32	.30	.28	.25	.23	.22
30°	-	.24	.25	.27	.29	.31	.32	.31	.30	.28	.26	.24	.23
25°	-	.24	.26	.27	.29	.30	.31	.31	.29	.28	.26	.25	.24
20°	-	.25	.26	.27	.28	.29	.30	.30	.29	.28	.26	.25	.25
15°	-	.26	.26	.27	.28	.29	.29	.29	.28	.28	.27	.26	.25
10°	-	.26	.27	.27	.28	.28	.29	.29	.28	.28	.27	.26	.26
5°	-	.27	.27	.27	.28	.28	.28	.28	.28	.28	.27	.27	.27
0°	-	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27	.27

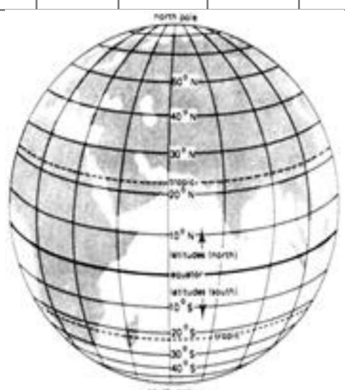

Figure 3.23. The latitude (Blaney and Criddle 1950).

Estimated ETo values

For rough ETo values, the table can be used for further calculations.

Table 3.26. Estimated ETo values (mm day^{-1}) (Blaney and Criddle 1950).

	Mean daily temperature		
Climatic zones	**Low (Less than 15 °C)**	**Medium (15-25 °C)**	**High (More than 25 °C)**
Desert/arid	4-6	7-8	9-10
Semi-arid	4-5	6-7	8-9
Sub-humid (Moist)	3-4	5-6	7-8
Humid	1-2	3-4	5-6

Table 3.27. Estimated ETo values using the Blaney–Criddle method (Blaney and Criddle 1950).

Months	**T-min (°C)**	**T-max (°C)**	**T-mean (°C)**	**p-value (Table 1.2)**	**ETo (mm day^{-1}) (p-value × (0.457 × T_{mean} + 8.128))**
January	6	12.3	9.15	0.22	2.708
February	6.2	12.8	9.5	0.24	2.993
March	7.8	15	11.4	0.27	3.601
April	10.2	17.8	14	0.3	4.358
May	14	22.4	18.2	0.32	5.263
June	18	26.7	22.35	0.34	6.236
July	20.5	29.8	25.15	0.33	6.475
August	20.7	29.6	25.15	0.31	6.083
September	18	26.5	22.25	0.28	5.123
October	14.4	21.8	18.1	0.25	4.100
November	10.4	17.3	13.85	0.22	3.181
December	7.2	13.6	10.4	0.21	2.705

Table 3.27 shows the estimated datasets acquired from the literature in standard conditions. The parameters were tested using the Blaney–Criddle model as this model is considered as an easier model to be used for the resulting data related to the ETo.

3.5.3. Crop Evapotranspiration (ETc)

Crop evapotranspiration is known as "The crop evapotranspiration free from disease, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieve complete production under the given climatic condition", and is denoted as ETc. The amount of water required which is transpired from crop and evaporated from soil must be compensated in which evapotranspiration plays a major role while the compensation of the evapotranspiration loss is known as crop water requirement of that specific field. Though the crop evapotranspiration and crop water requirement provide similar and same level values, however, crop water requirement is the amount of water that are required by the crops at the season under specific soil and field conditions, while crop evapotranspiration is the amount of water that is lost through the evapotranspiration process. The irrigation crop water requirement of the specific crop and its relevant parameters are the difference between effective precipitation and crop water requirement. The irrigation water requirement of the specific crop must be considered with salt water leaching and water compensation of an un-uniformity application (Allen et al. 1998).

The climatic data is considered to calculate the crop evapotranspiration and crop resistance variables, air resistance parameters, and albedo by using the P–M model. Due to a considerable gap in information about various crops, the latest P–M model can be utilized to calculate the standard reference crop evapotranspiration (ETo) values at the given region.

A significant and dependent factor related to the crop evapotranspiration known as crop coefficient (kc) is an experimental ratio determined as $ETc\ ETo^{-1}$. Crop coefficient is the relation of the ETc to ETo or $ETc = kc \times ETo$. The differences in different variables including aerodynamic resistance, albedo, plant leaf stomatal characteristics, and leaf anatomy cause the crop evapotranspiration to increase or decrease that of the reference crop evapotranspiration within the same region and climatic zone. As crop plant grows provided the optimum conditions, their characteristics also changes within the growing season, so the kc also changes from the day of sowing to the maturity and finally the harvest (Allen et al. 1998).

3.6. Data Analysis: Comparison between H–S and B–C models for ETo calculation at Campobasso (W1, W2, W3 and W4)

The following figures presents the installation of the solar fertigation system in the test fields which was tested with the help of the collected data in Two (02) different regions. The tests in the first region (Molise region) are presented which is as follows:

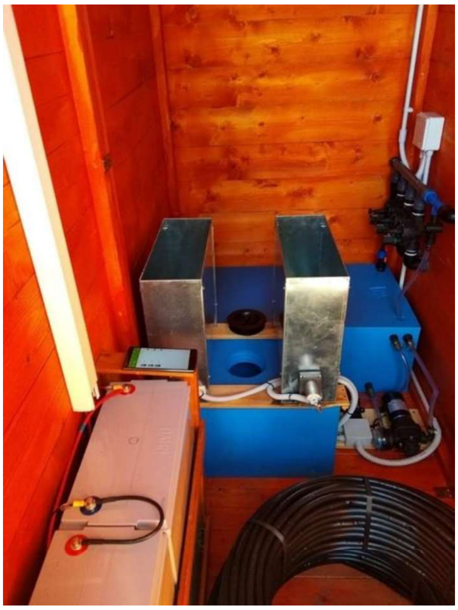

Figure 3.24. Solar fertigation system installation at region-1 (Molise region – Campobasso).

Figure 3.25. Solar fertigation system installation at region-1 (Molise region – Campobasso).

Figure 3.26. Solar fertigation system installation at region-1 (Molise region – Campobasso).

The following analysis presents the comparison of the best equation among the H–S and B–C models by using the collected data from 2019 to 2020 from the first region (Molise region – Campobasso). Some systematic errors were found and corrected for a few weather stations (W1–Campobasso East; W2–Campobasso North; W3–Campobasso West; W4–Campobasso South) regarding the temperature and solar radiation, after comparing it with the climate data analyzed by other researchers (Gentilucci et al. 2021; Antonio et al. 2015; Keswani et al. 2020; Abioye et al. 2020).

The monthly ETo data was estimated by using the both H–S and B–C models in order to analyses the differences and evaluate the best ETo method which required minimum crop and environmental parameters. First, monthly data from 2019 to 2021 for each weather station were estimated using both the models (Figure 3.27; Figure 3.28; Figure 3.29).

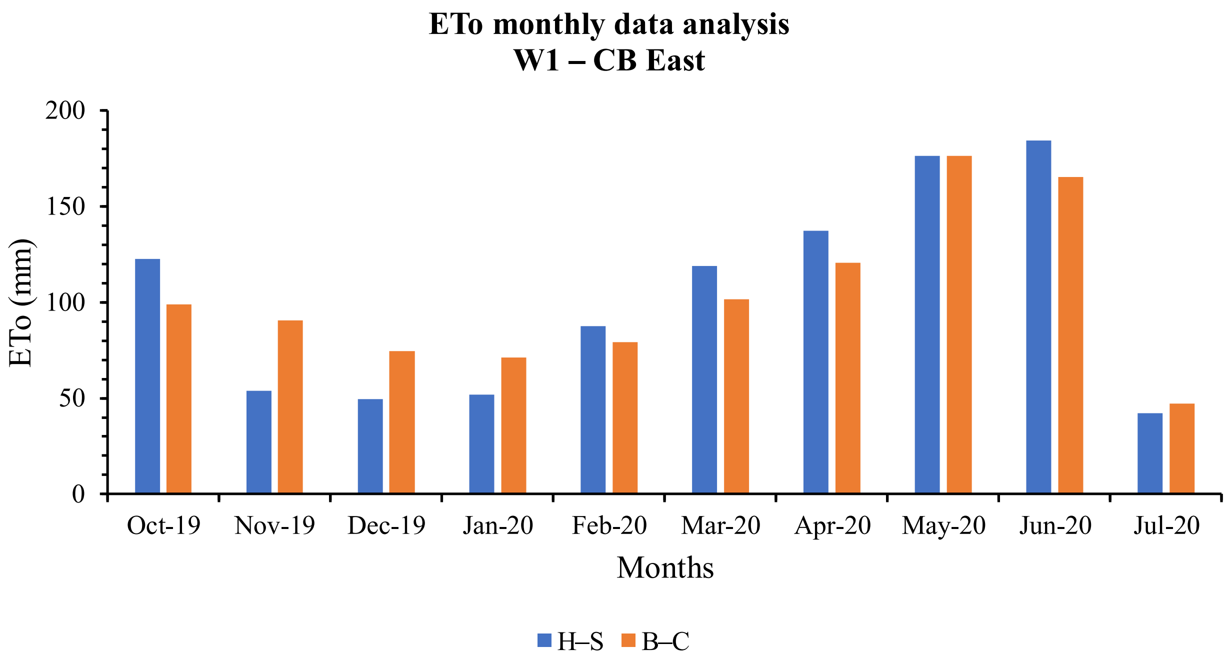

Figure 3.27. Monthly ETo estimation using the H–S and B–C Models at the W1 – CB East are estimated from October 2019 to July 2020.

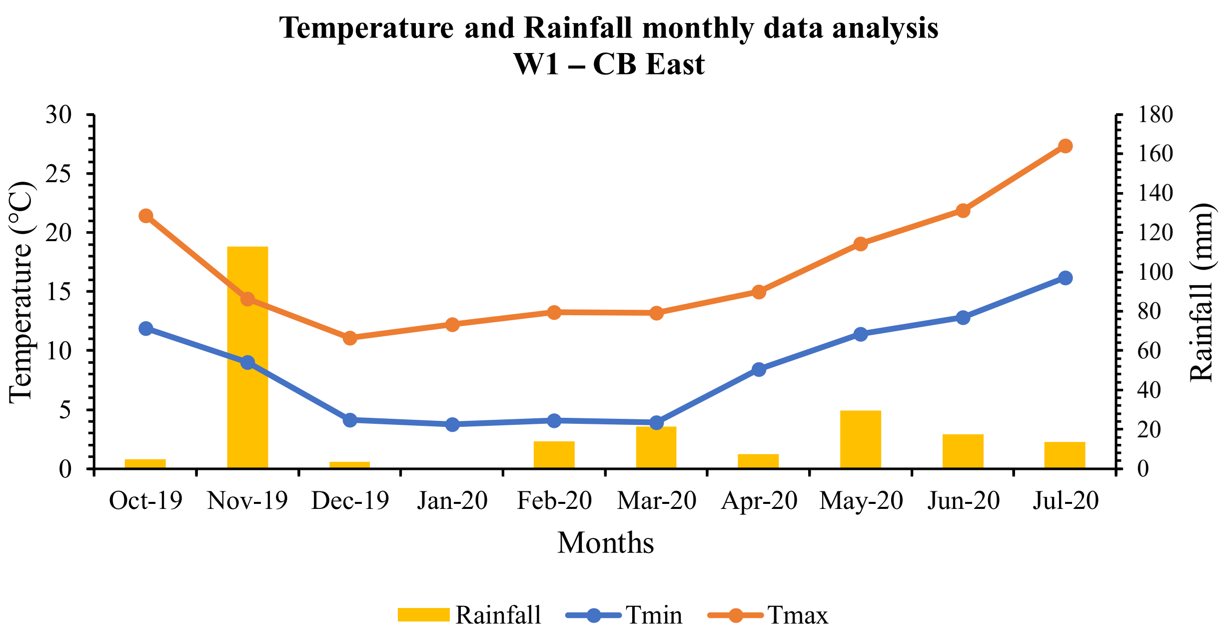

Figure 3.28. Monthly temperature and rainfall estimation at the W1 – CB East are estimated from October 2019 to July 2020.

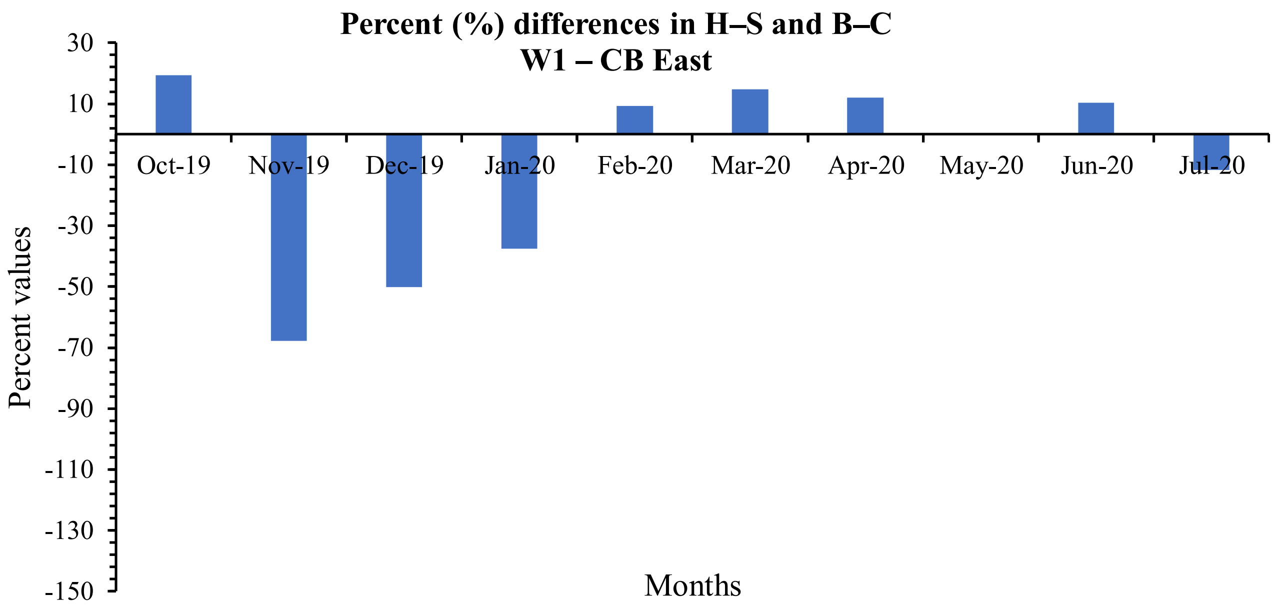

Figure 3.29. Monthly differences in the H–S and B–C Models at the W1 – CB East are estimated from October 2019 to July 2020.

The initial analysis (Figure 3.27) revealed that the ETo estimated with H–S model was mostly similar to the data collected with the B–C model at the W1–CB East station, with the data that just differs by a few mm on monthly basis. In October, November and December 2019, some significant differences could be seen due to the temperature and solar radiation values in these specific months. Figure 3.28 shows the highest monthly average Rainfall in November 2019 and Temperature in July 2020 which highly impacted the rate of ETo. However, Figure 3.29 shows the percent differences in both H–S and B–C models with the highest difference of negative 67.69% in November 2019. Although both of the models showed good agreement, there consists a possibility of recording high differences.

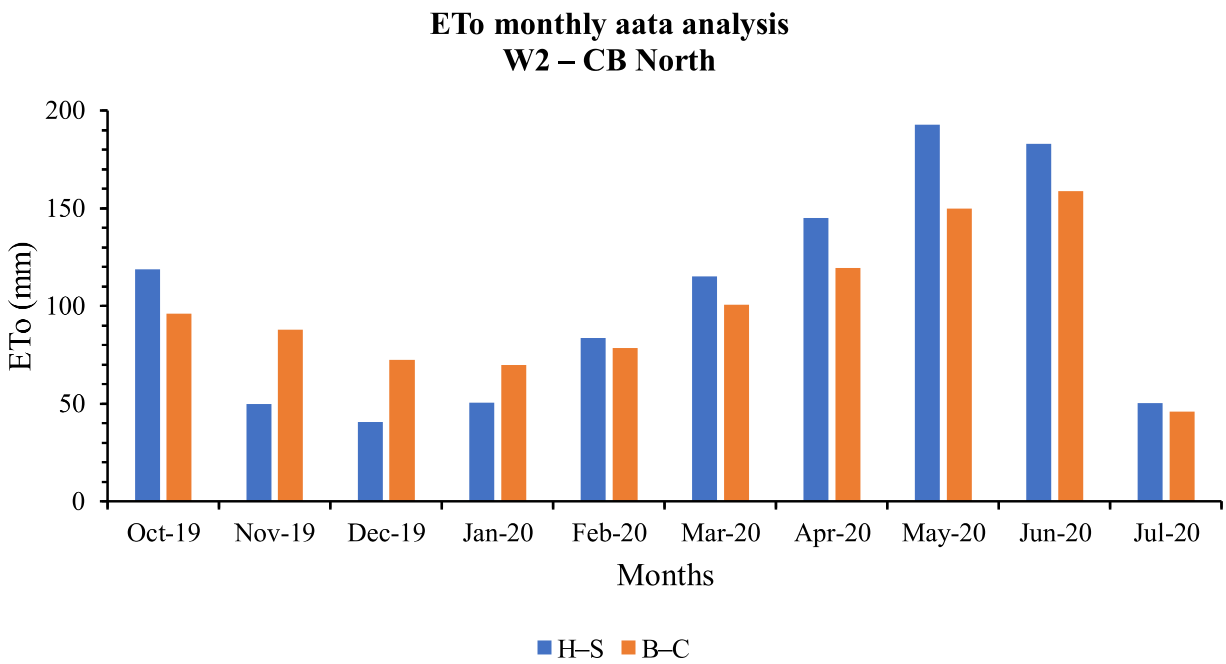

Figure 3.30. Monthly ETo estimation using the H–S and B–C Models at the W2 – CB North are estimated from October 2019 to July 2020.

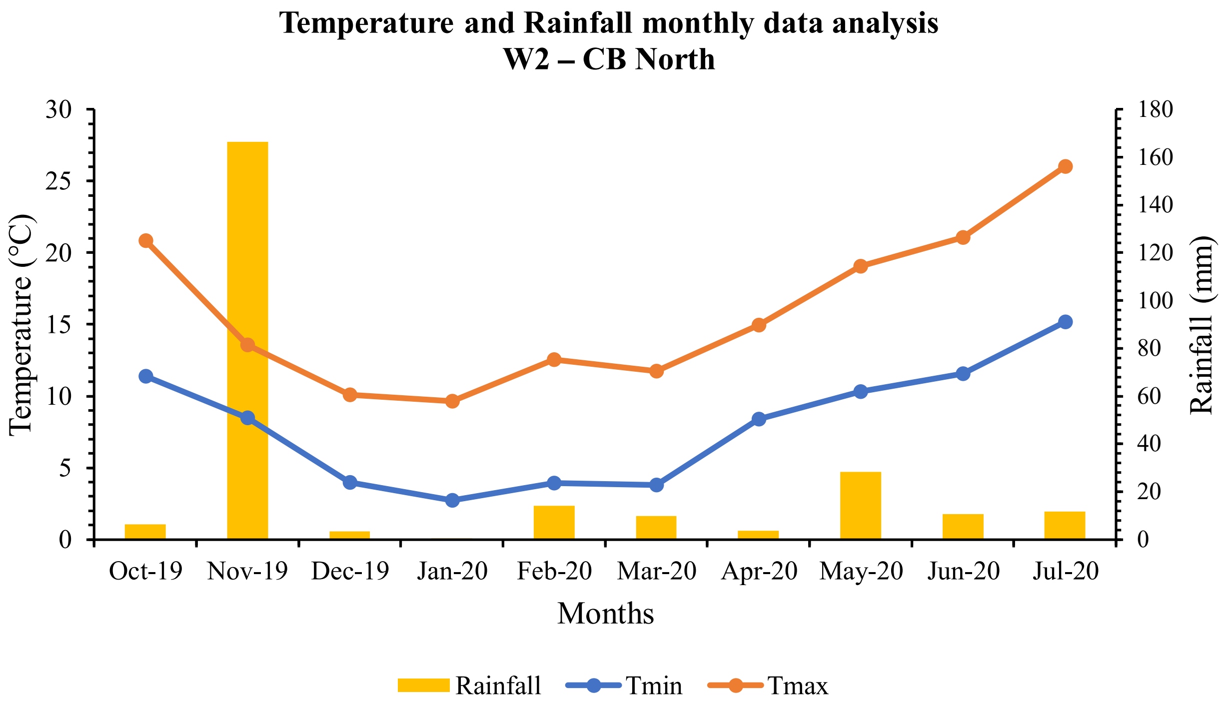

Figure 3.31. Monthly temperature and rainfall estimation at the W2 – CB North are estimated from October 2019 to July 2020.

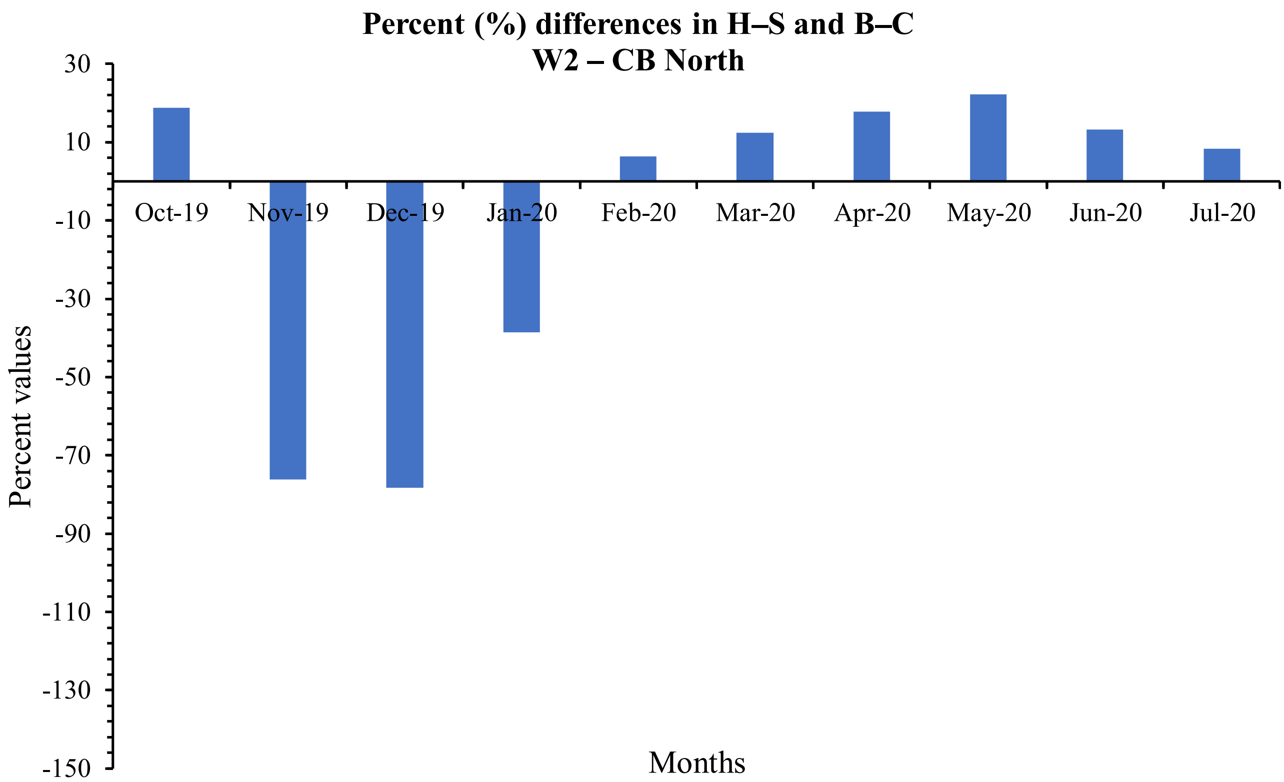

Figure 3.32. Monthly differences in the H–S and B–C Models at the W2 – CB North are estimated from October 2019 to July 2020.

The analysis (Figure 3.30) showed that the ETo estimated with the H–S model was mostly similar to the data collected with the B–C model at the W2–CB North station, with the data that just differs by a few mm on monthly basis. In October-2019, November-2019, December-2019 and May-2020, some significant differences are highlighted due to the temperature and solar radiation values. Figure 3.31 shows the highest monthly average Rainfall in November 2019 and Temperature in July 2020 which effected the rate of ETo in those months. However, Figure 3.32 shows the percent differences in both H–S and B–C models with the highest difference of negative 78.25% in December 2019. Although both of the models showed a good correlation, there consists a possibility of recording high differences depending on the region.

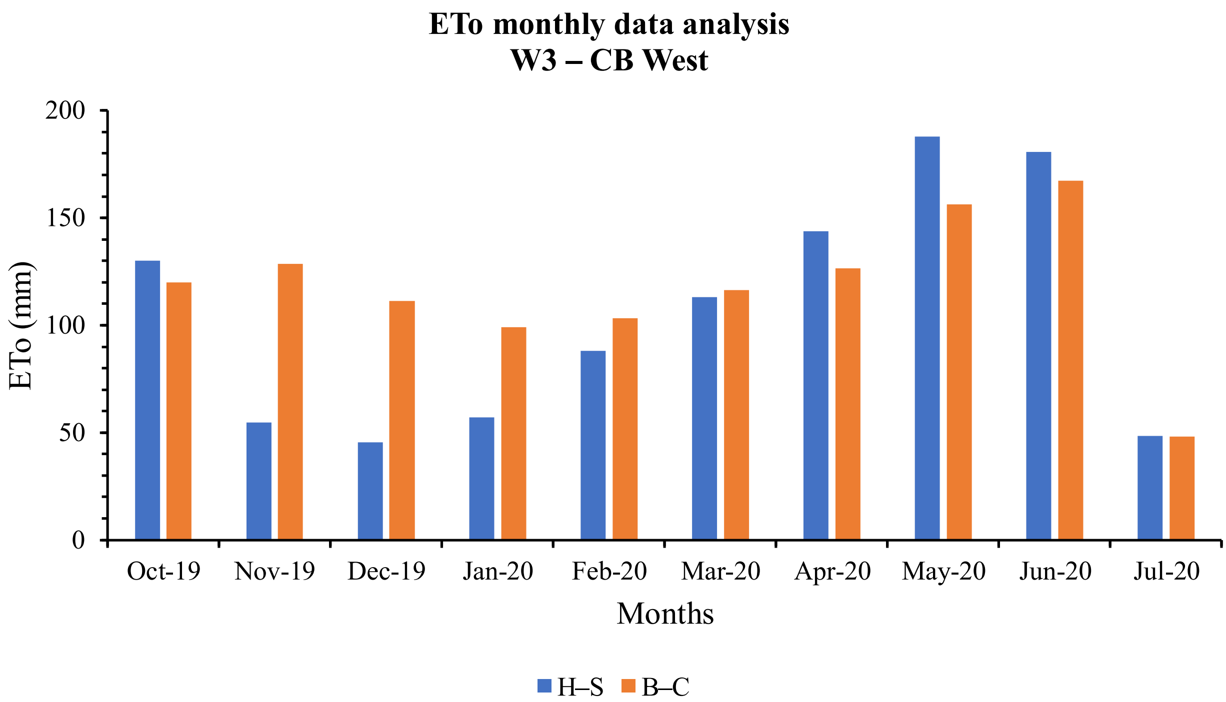

Figure 3.33. Monthly ETo estimation using the H–S and B–C Models at the W3 – CB West are estimated from October 2019 to July 2020.

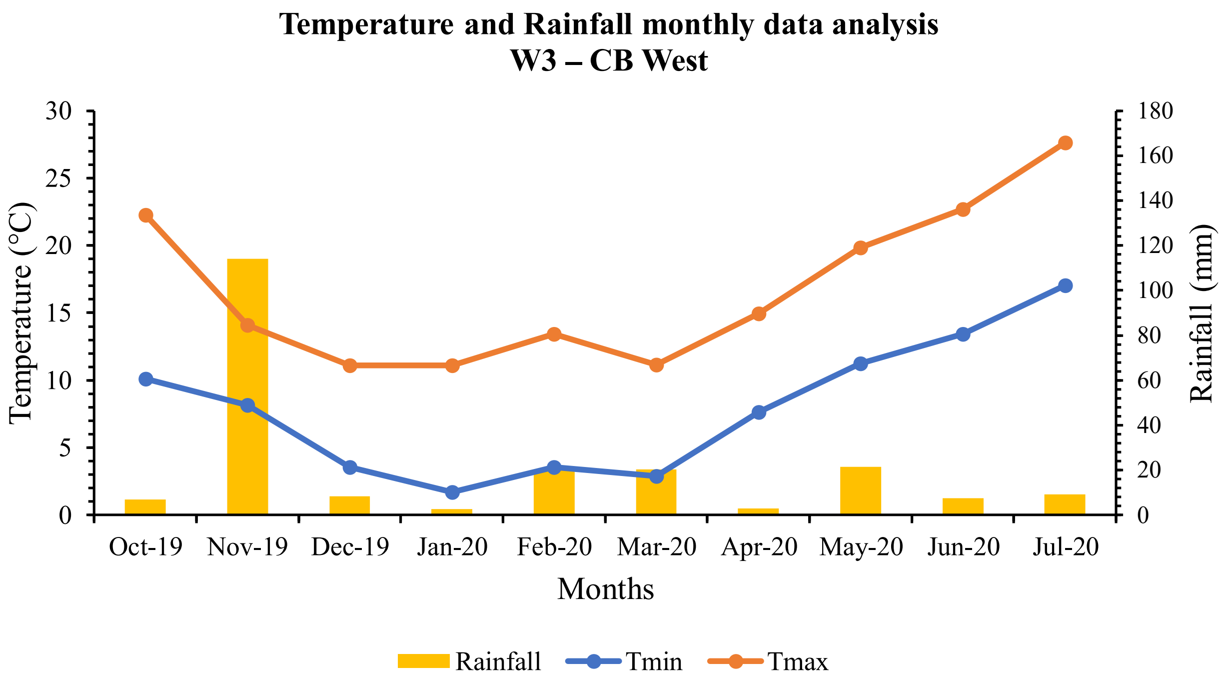

Figure 3.34. Monthly temperature and rainfall estimation at the W3 – CB West are estimated from October 2019 to July 2020.

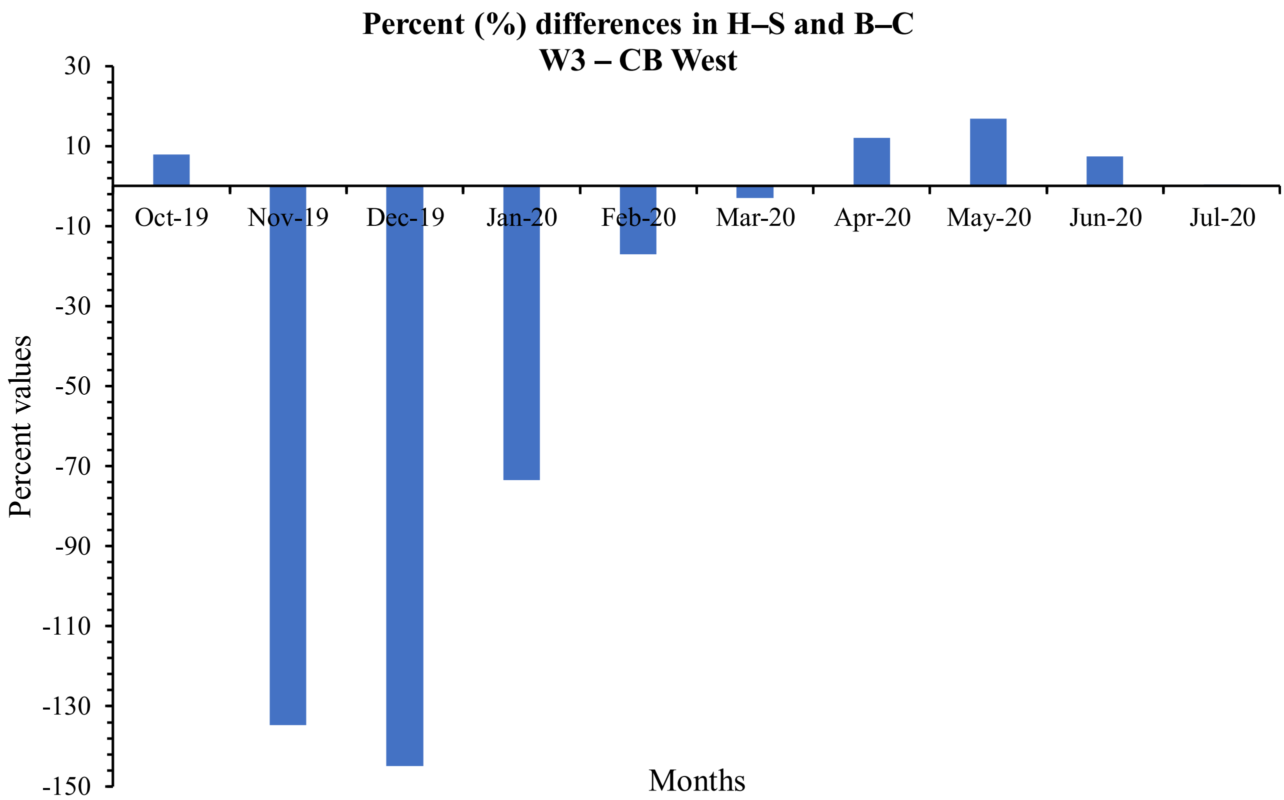

Figure 3.35. Monthly differences in the H–S and B–C Models at the W3 – CB West are estimated from October 2019 to July 2020.

The analysis (Figure 3.33) showed that the ETo estimated with the H–S model was mostly similar to the data collected with the B–C model at the W3 – CB West station, with the data that just differs by a few mm on monthly basis. In November-2019, December-2019 and January-2020, some significant differences of about 50mm monthly differences are recorded due to the temperature and solar radiation data. Figure 3.34 shows the highest monthly average Rainfall in November 2019 and Temperature in July 2020 (as according to the W1 and W2 stations) which significantly affected the rate of ETo to increase or decrease, respectively. Figure 3.35 shows the percent differences in both H–S and B–C models with the highest difference of negative 144.90% in December 2019 and lowest in July 2020 with positive 0.35%. In W3 station, both of the models showed a good correlation while it shows that there consists a possibility of recording high differences among these models.

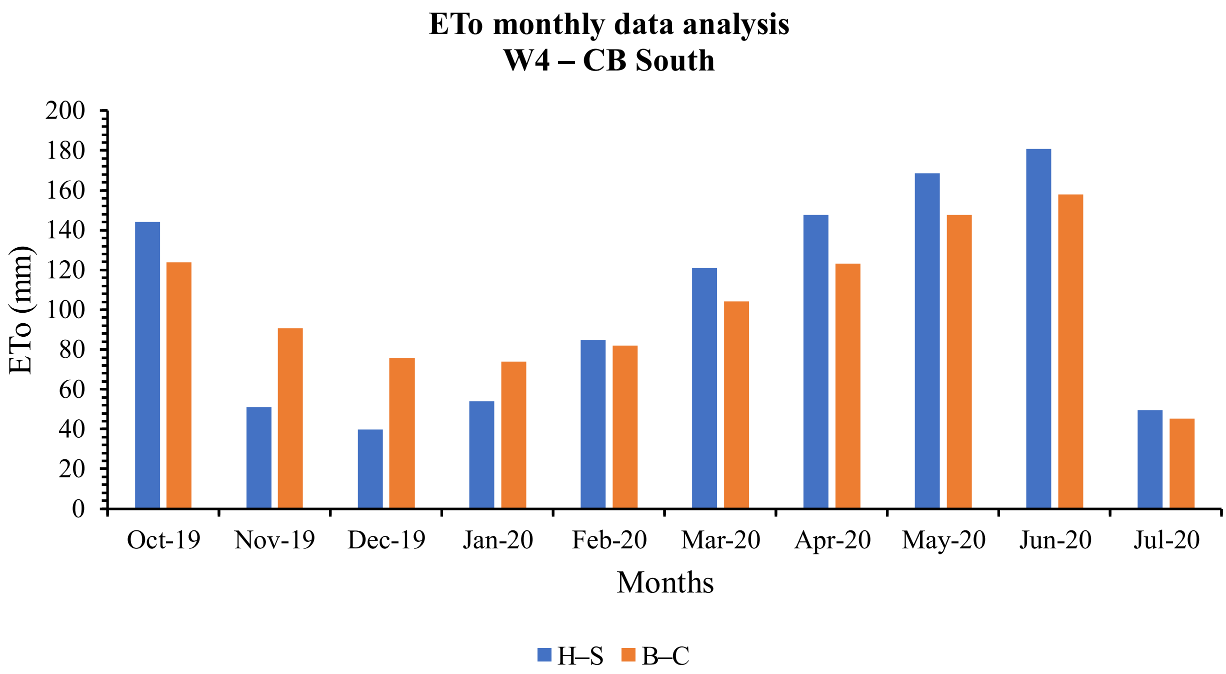

Figure 3.36. Monthly ETo estimation using the H–S and B–C Models at the W4 – CB South are estimated from October 2019 to July 2020.

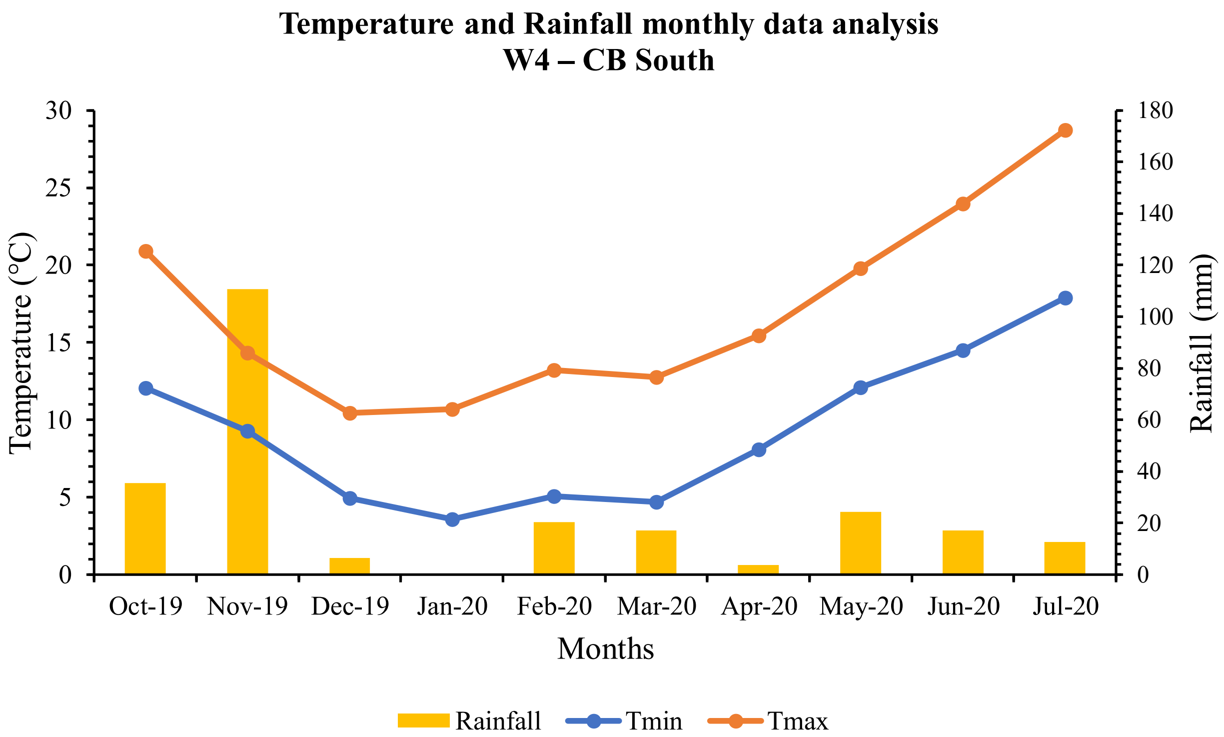

Figure 3.37. Monthly temperature and rainfall estimation at the W4 – CB South are estimated from October 2019 to July 2020.

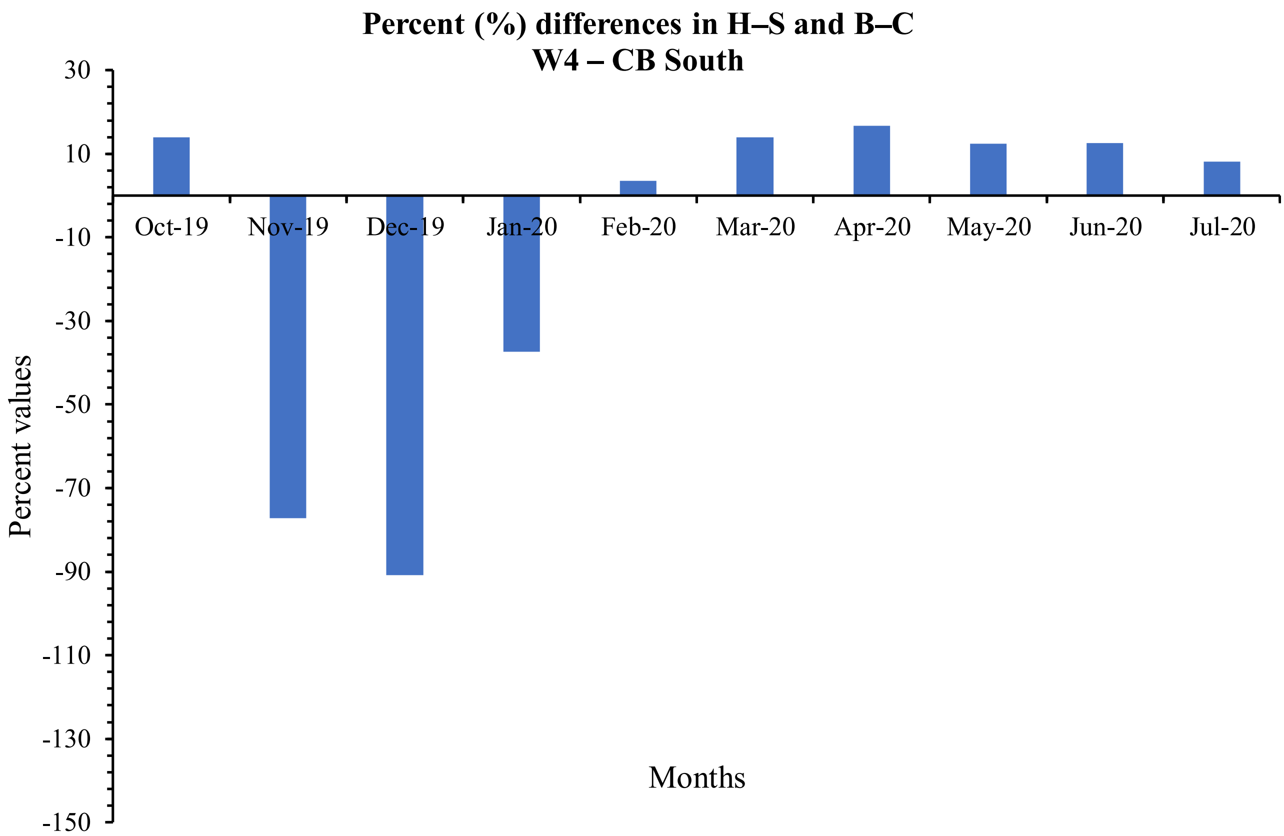

Figure 3.38. Monthly differences in the H–S and B–C Models at the W4 – CB South are estimated from October 2019 to July 2020.

The analysis (Figure 3.36) showed the ETo estimation using the H–S model with similar data to the B–C model at the W4 – CB South station, with the data that just differs by a few mm on monthly basis. Highest ETo was revealed in April, May and June 2020. Figure 3.37 shows the highest monthly average Rainfall in November 2019 and Temperature in July 2020 (as according to the W1, W2 and W3 stations) which significantly affected the rate of ETo to increase or decrease, respectively. Figure 3.38 shows the percent differences in both H–S and B–C models with the highest difference in December 2019 and lowest in February 2020. Both models showed a good correlation in between each other while there is yet a possibility of recording high differences among these models in different regions.

3.7. Data analysis: Comparison between H–S and B–C models for ETo calculation at Apulia region (W1, W2 and W3)

The following analysis presents the comparison of the best equation among the H–S and B–C models by using the collected data in 2021 from the second region: Apulia region (W1–Montemesola; W2–Castellaneta; W3–Marina di Ginosa). Some systematic errors were found and corrected at the weather station which were related to the temperature and solar radiation, after comparing it with the climate data analyzed by researchers (Gentilucci et al. 2021; Antonio et al. 2015; Keswani et al. 2020; Abioye et al. 2020).

The following figures present the installation of the solar fertigation system to collect the required data at the second (2nd) region (Apulia region) which is presented as follows:

Figure 3.39. Solar fertigation system installation at region-2 (Apulia region).

Figure 3.40. Solar fertigation system installation at region-2 (Apulia region).

Figure 3.41. Solar fertigation system installation at region-3 (Apulia region).

The monthly ETo data was estimated by using the both H–S and B–C models in order to analyses the differences and evaluate the best ETo method which required minimum crop and environmental parameters. First, monthly data in 2021 for the weather station was estimated using both the models (Figure 3.42; Figure 3.43; Figure 3.44).

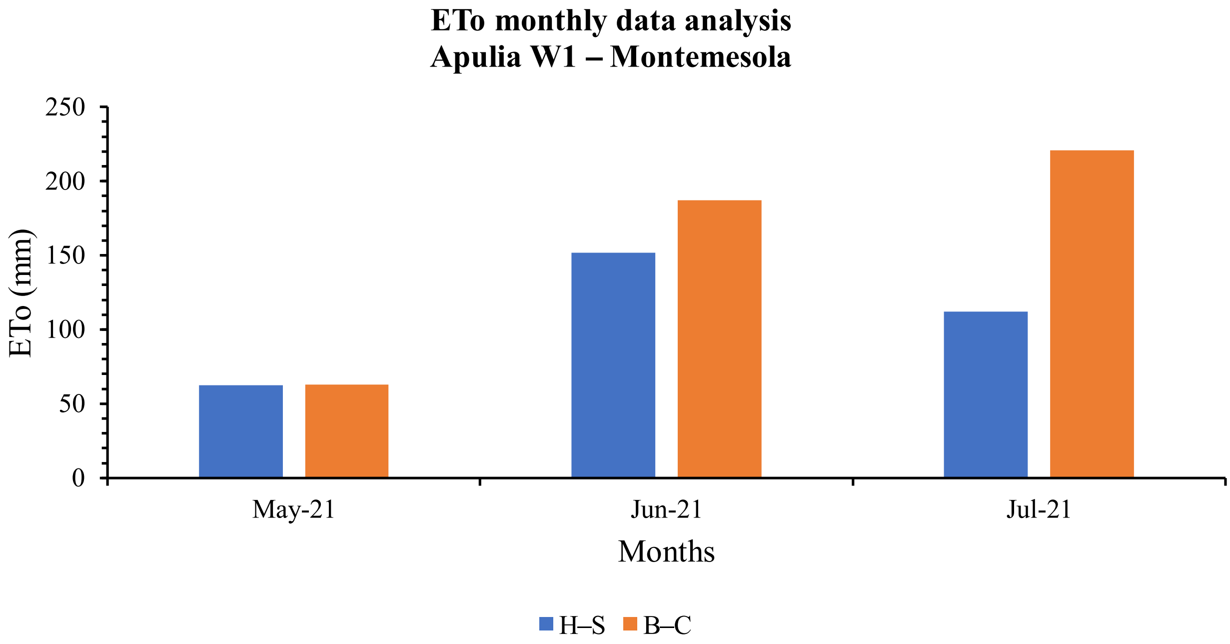

Figure 3.42. Monthly ETo estimation using the H–S and B–C Models at the Apulia region W1 – Montemesola are estimated from May to July 2021.

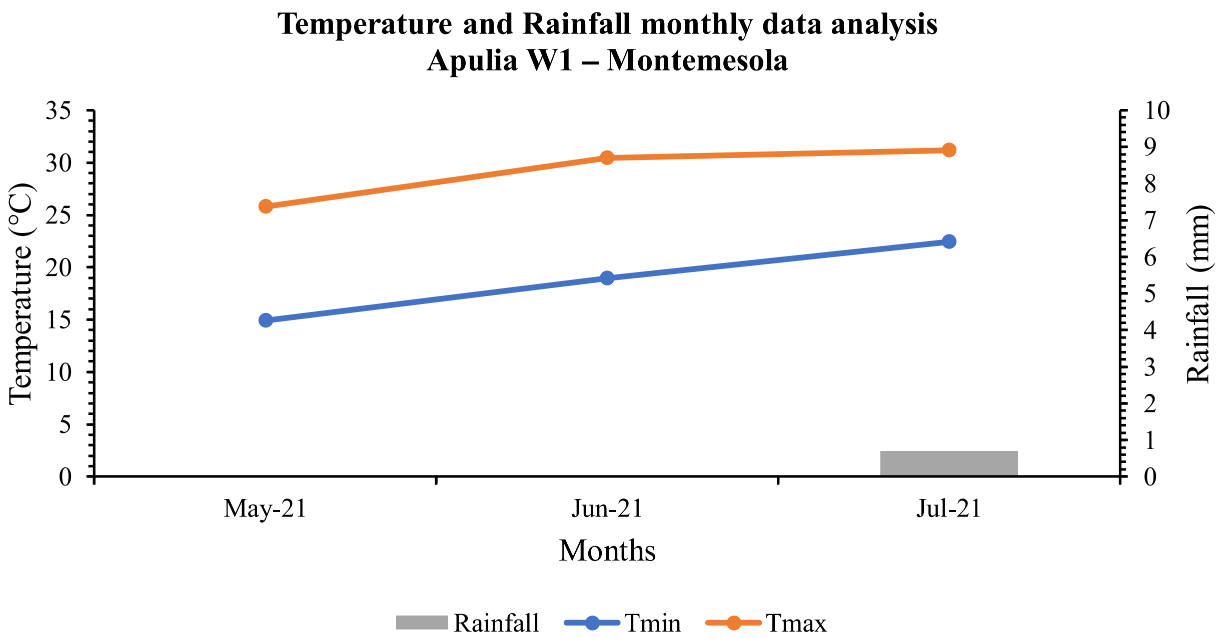

Figure 3.43. Monthly temperature and rainfall estimation at the Apulia region W1 – Montemesola are estimated from May to July 2021.

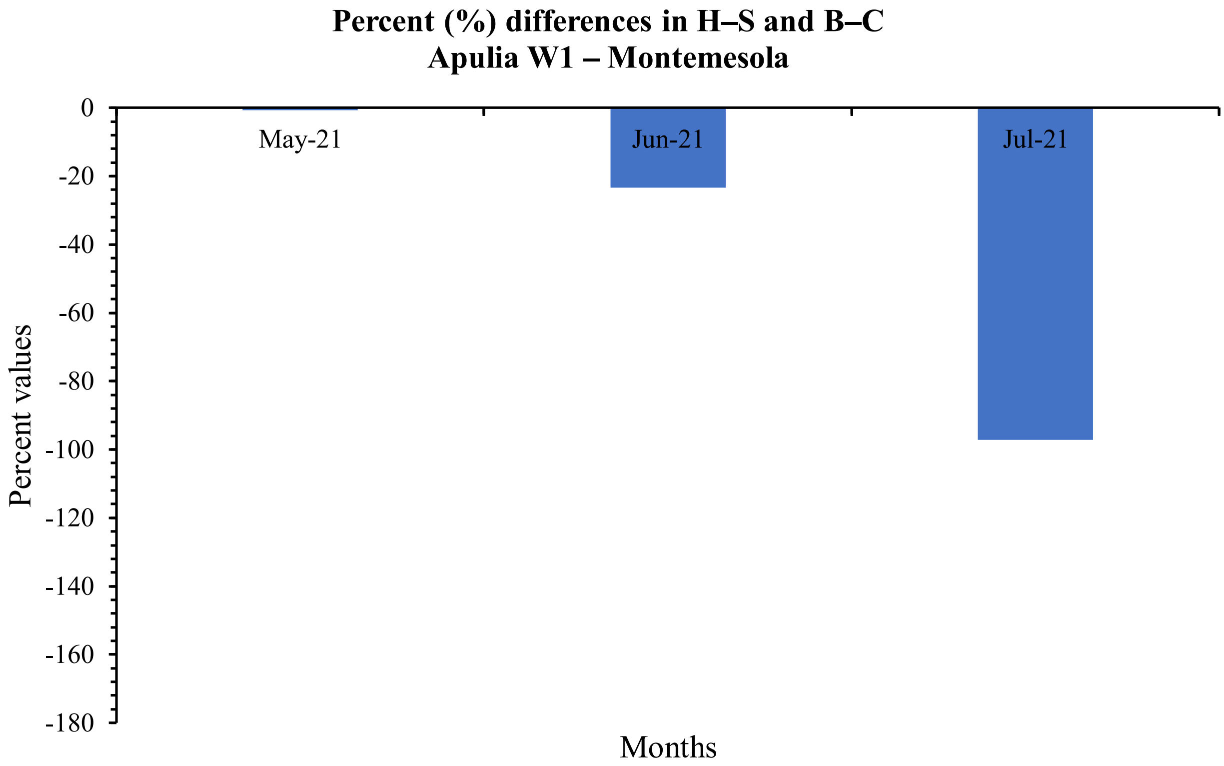

Figure 3.44. Monthly differences in the H–S and B–C Models at the Apulia region W1 – Montemesola are estimated from May to July 2021.

The initial analysis (Figure 3.42) revealed that the ETo estimated with H–S model was mostly similar to the data collected with the B–C model at the W1–Apulia region of the Montemesola, with the data that just differs by a few mm on monthly basis. In May and June 2021, some significant differences could be seen due to the temperature and solar radiation data. Figure 3.43 shows the highest monthly average Rainfall and Temperature in July 2021 which highly impacted the rate of ETo. However, Figure 3.44 shows the percent differences in both H–S and B–C models with the highest difference of negative 97.22% in July 2021.

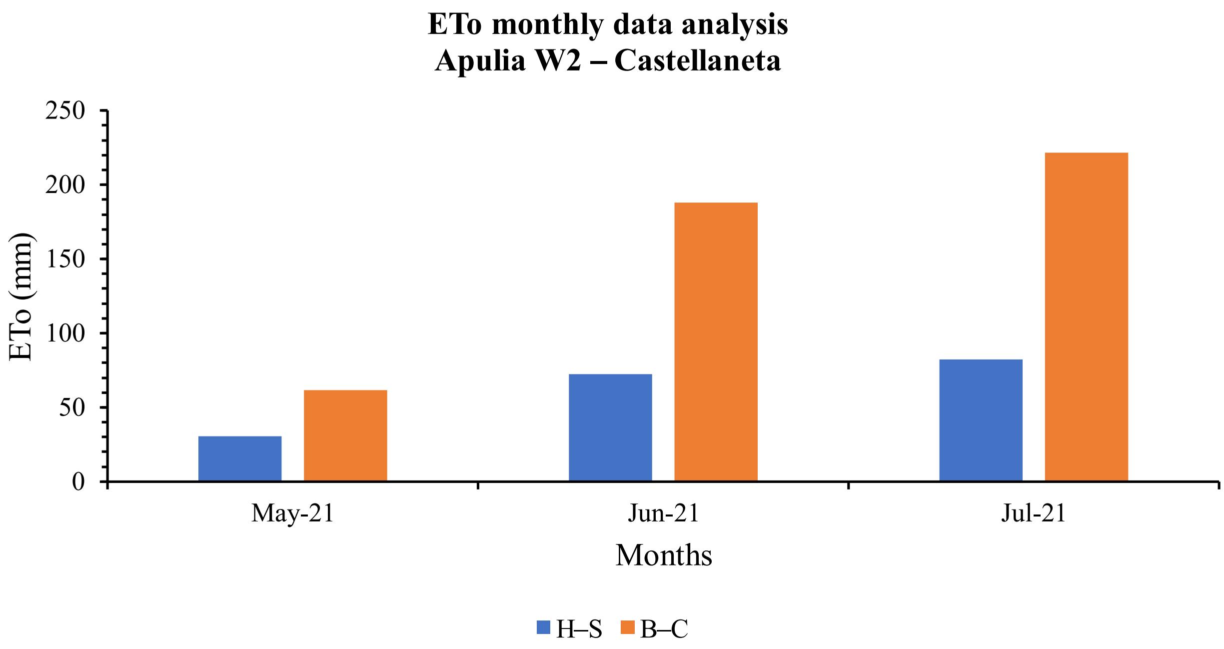

Figure 3.45. Monthly ETo estimation using the H–S and B–C Models at the Apulia region W2 – Castellaneta are estimated from May to July 2021.

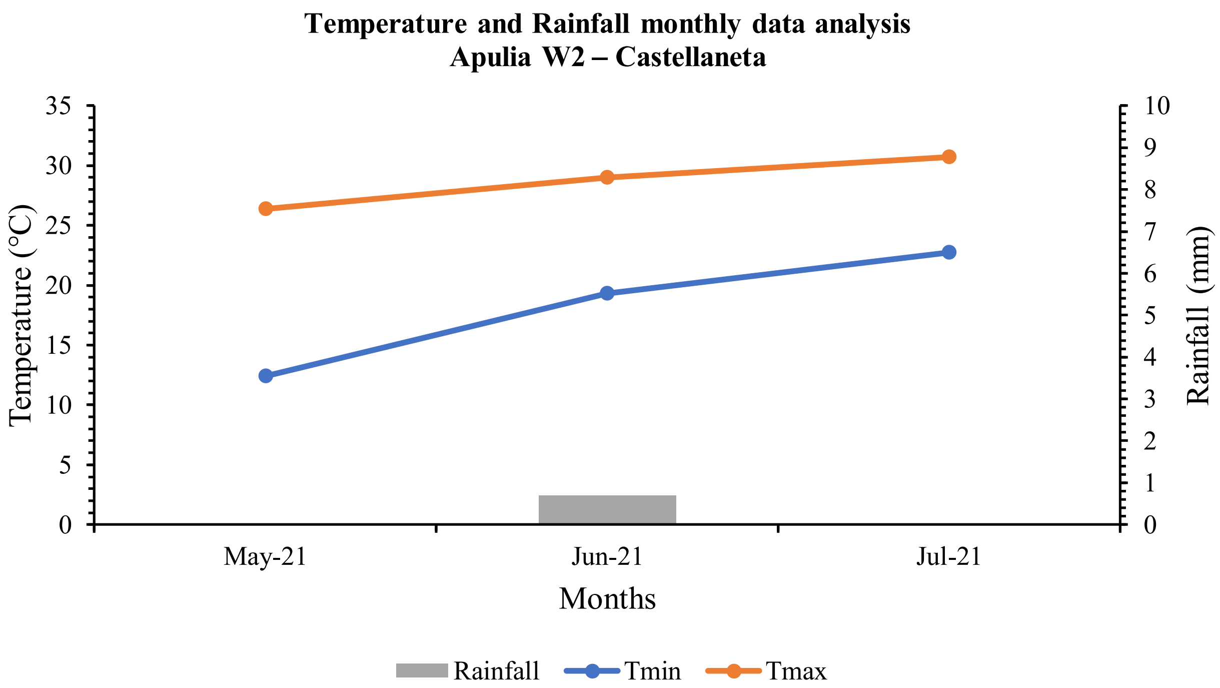

Figure 3.46. Monthly temperature and rainfall estimation at the Apulia region W2 – Castellaneta are estimated from May to July 2021.

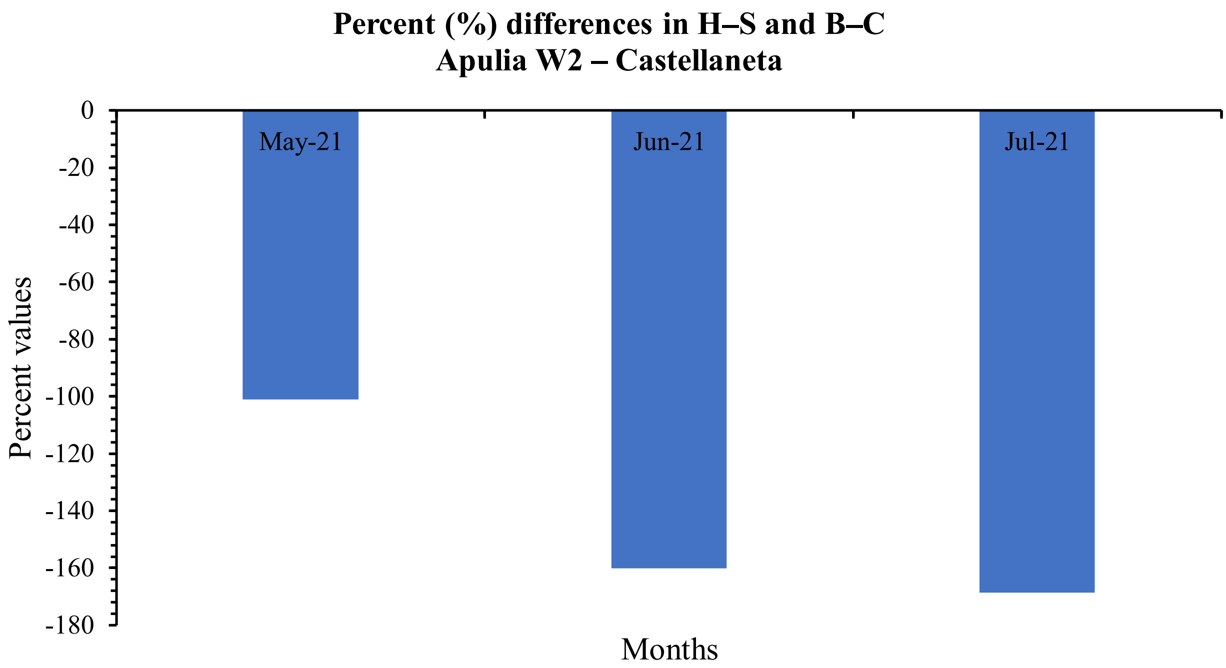

Figure 3.47. Monthly differences in the H–S and B–C Models at the Apulia region W3 – Castellaneta are estimated from May to July 2021.

The analysis illustrated in the Figure 3.45 recorded that the ETo estimated with H–S model was mostly similar to the data collected with the B–C model at the W2–Apulia region of the Castellaneta, with the data that just differs by a few mm on monthly basis. In June and July 2021, some significant differences could be seen due to the temperature and solar radiation values. Figure 3.46 shows the highest monthly average Rainfall in June 2021 and Temperature in July 2021 which effecting the ETo rate. Figure 3.47 shows the percent differences in both H–S and B–C models with the highest difference in July 2021.

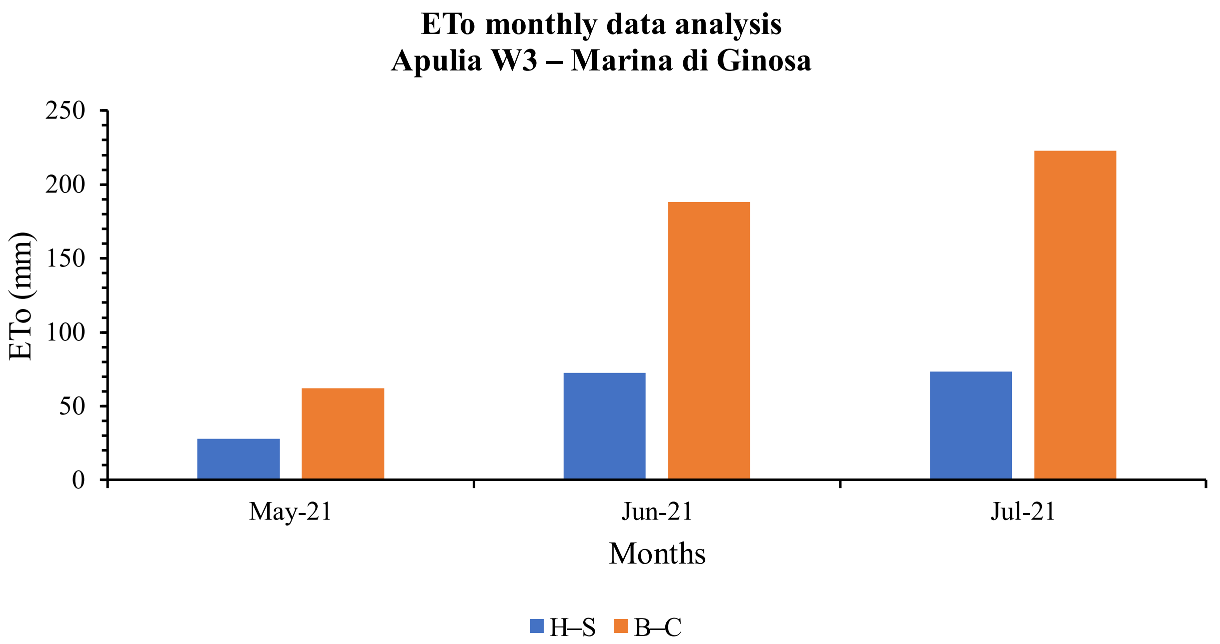

Figure 3.48. Monthly ETo estimation using the H–S and B–C Models at the Apulia region W3 – Marina di Ginosa is estimated from May to July 2021.

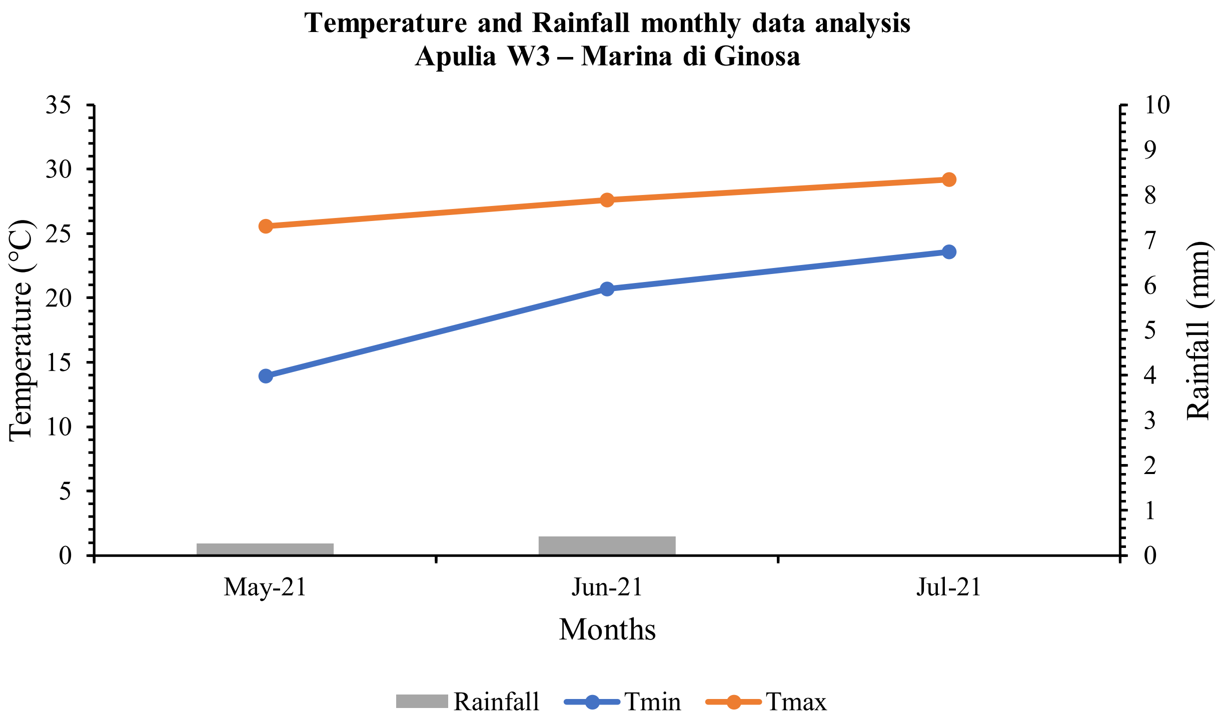

Figure 3.49. Monthly temperature and rainfall estimation at the Apulia region W3 – Marina di Ginosa are estimated from May to July 2021.

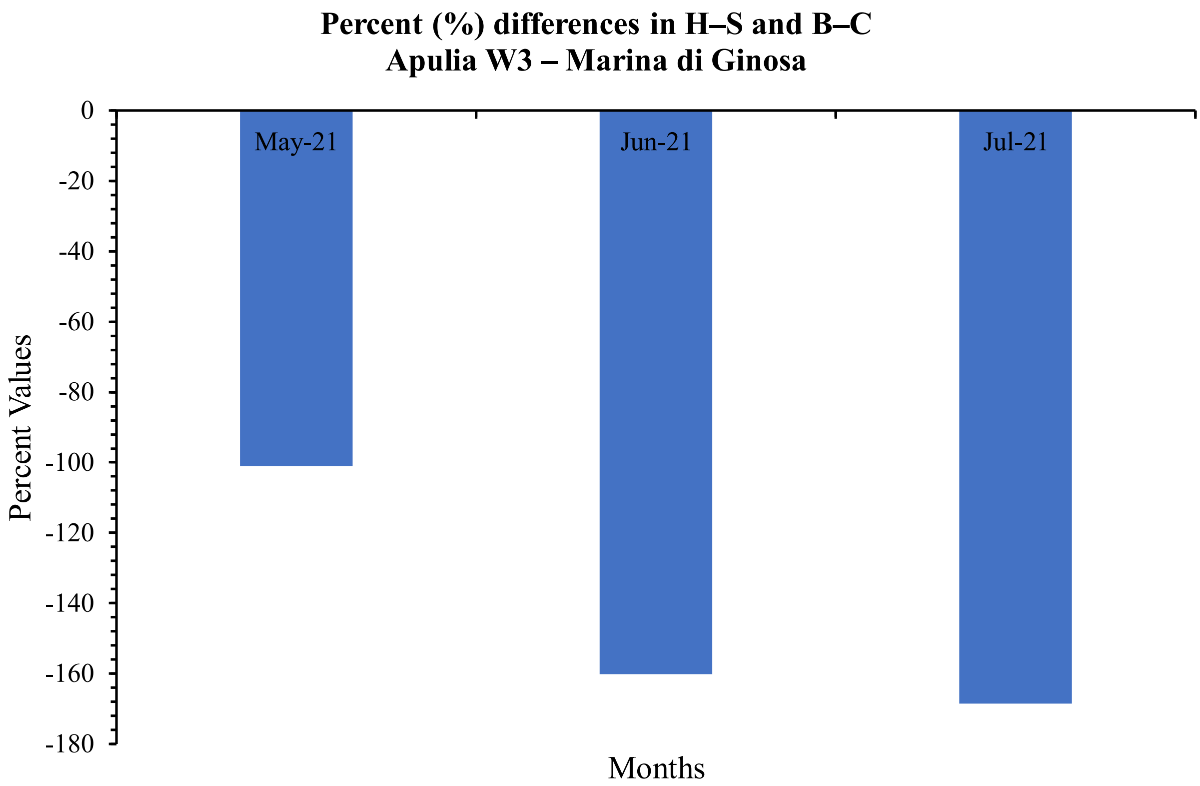

Figure 3.50. Monthly differences in the H–S and B–C Models at the Apulia region W3 – Marina di Ginosa are estimated from May to July 2021.

The Figure 3.48 showed that the ETo estimated with H–S data was highly correlated to the B–C data at the W3–Apulia region of the Marina di Ginosa, with the data that just differs by a few mm on monthly basis. In June and July 2021, some differences are recorded due to the temperature data. Figure 3.49 shows the highest monthly average Rainfall in May 2021 and Temperature in July 2021 affecting the rate of ETo. However, Figure 3.50 shows the percent differences in both H–S and B–C models with the highest difference in July 2021. Although both of the models showed good correlation, there consists a possibility of recording high differences in different regions.

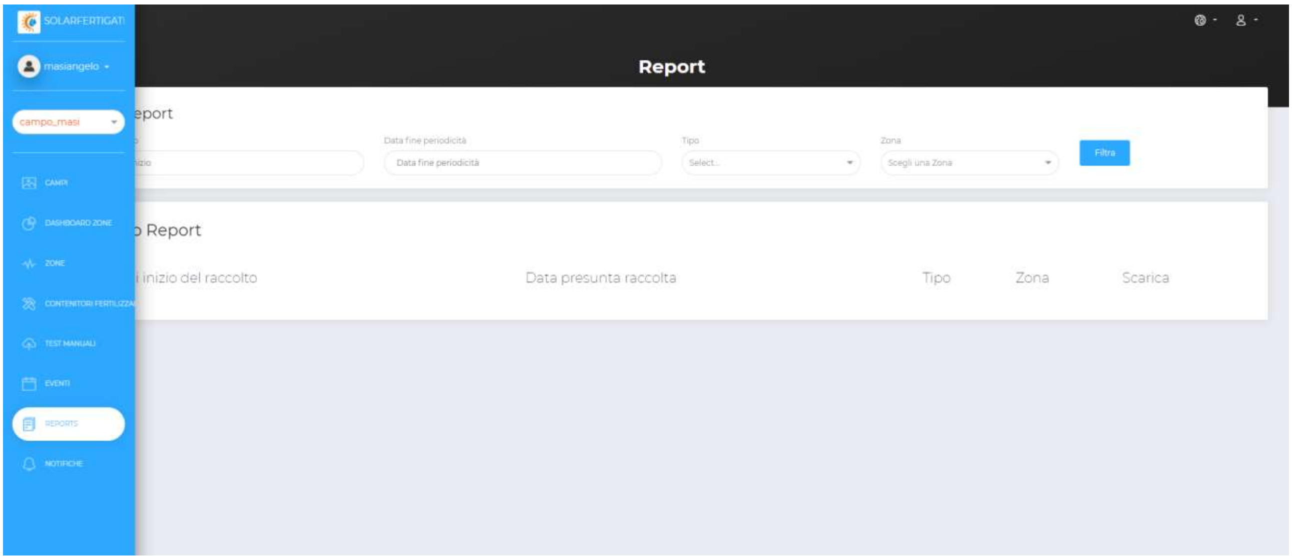

Figure 3.51. Finally, the report is presented by the solar fertigation application with all the assessments and analysis.

3.8. Summary

Chapter 3 discussed several important and accurate environmental, and rainfall data collection methods. While the official resources and systematic environmental factors collected precise crop yield estimation depending on the meteorological data acquisition. Chapter 3 further presented development of the dataset for the particular years ranging from 2019-2021 using the solar fertigation system and official meteorological resources. The dataset acquired in these years were validated, and properly corrected that resulted to fill the recorded gaps. A compliment for few techniques to measure the evapotranspiration recognized by the FAO56 Manual and P–M model was considered as the highly reliable resource of measuring the reference evapotranspiration in Italian regions. Based on the calculations of these empirical methods, the acquired meteorological data integrated with the coefficient of variance tested by Seifi et al. (2020) are able to deliver precise measurements of the ETo in a diverse set of crops in Italy.

Chapter 4

Conclusion

Agricultural production must promote the implementation of farming practices and the adoption of highly sustainable models in order to support resilience and competitiveness. From this perspective, this thesis has analyzed the evapotranspiration processes of different crops in seven climatic regions, such as Molise region (Campobasso East, Campobasso North, Campobasso West, and Campobasso South), and Apulia region (Montemesola, Castellaneta and Marina di Ginosa) to understand the potential benefits of the implementation of an on-farm solar fertigation system. The study has developed a database for several crops.

Additionally, uncontrolled irrigation withdrawal and non-efficient fertigation processes lead to a decrease in irrigation resources quantity and quality. The irrigation quality deterioration is the major cause by in-depth filtration of fertilizers and other products inside the water that primarily affect the crop development and growth. For H–S model, the highest monthly ETo was revealed as 192 mm at Campobasso North in May 2020, while the lowest of which was recorded as 40 mm at the Campobasso North in December 2019. For B–C model, the highest monthly ETo was revealed 178 mm at the Campobasso East in May 2020, while the lowest of which was recorded as 42 mm at the

Campobasso East in July 2020. The temperature and rainfall monthly correlation showed a linear trend in all the study period. The high rainfall recorded was 166 mm in November 2019, while the lowest was recorded as 0 mm in January 2020.

Environmental data, crop data and solar fertigation data were collected by the soil moisture sensors installed into the fields, sensors made up by Politecnico of Bari, and transferred to the central unit. The crop ET level was also taken into account by the crop sensors installed near to the root zone. The sensors were precisely monitoring the crop ET levels and forecast with accurate meteorological data. Both, the sensors and the solar fertigation system were accurately estimating the crop ET which is an important aspect of the study, not just for irrigation assistance and freshwater utilization development, but also for the local and global climate effect research. An unparallel model for crop ET calculation is developed based on crop and environmental datasets, without impacting the precision of the measurements.

The solar fertigation system successfully managed irrigation and fertilization in an appropriate mode, depending on the soil moisture levels. Considerable reduction in energy consumptions were achieved due to the photovoltaic panels, and for the high number of sunny days, more than 250 per year. Furthermore, this thesis compared reference evaporanspiration (ETo) using H–S and B–C models. The data were analyzed in terms of daily temperature, rainfall, relative humidity, UV–radiation, and air speed and were provided the correlation among the H–S and B–C models in different climatic regions.

Overall, this thesis highlights how an innovative technology may contribute to mitigation of climate change. Solar fertigation may contribute to reduce irrigation water, to lower the consumption of energy for pumping purposes, a reduced use of fertilizers. All these positive features may contribute to increase the income of farmers, to stabilize crop yields, and to reduce the risk of groundwater pollution caused by inappropriate irrigation management.

Chapter 5

References

1. Abd El-Wahed MH, Al-Omran AM, Hegazi MM, Ali MM, Ibrahim YAM, EL Sabagh A. Salt Distribution and Potato Response to Irrigation Regimes under Varying Mulching Materials. Plants 2020; 9:701. https://doi.org/10.3390/plants9060701

2. Abdelfatah N, Abd-Elmageed H, Ibrahim M. A model for predicing and improving irrigation water management in Egypt – Corn as a case study. Misr Journal of Agricultural Engineering 2021; 39:15-36. https://doi.org/10.21608/mjae.2021.96346.1047

3. Abdelkhalik A, Pascual B, Nájera I, Baixauli C, Pascual-Seva N. Regulated Deficit Irrigation as a Water-Saving Strategy for Onion Cultivation in Mediterranean Conditions. Agronomy 2019(a); 9:521. https://doi.org/10.3390/agronomy9090521

4. Abdelkhalik A, Pascual-Seva N, Nájera I, Giner A, Baixauli C, Pascual B. Yield response of seedless watermelon to different drip irrigation strategies under Mediterranean conditions. Agricultural Water Management 2019(b); 212:99–110. https://doi.org/10.1016/j.agwat.2018.08.044

5. Abdelraouf RE, El-Shawadfy MA, Hashem FA, Bakr, BMM. Effect of deficit irrigation strategies and organic mulching on yield, water productivity and fruit quality of navel Orange under arid regions conditions. Plant Archives 2020; 20:3505-3518.

6. Abioye EA, Abidin MSZ, Mahmud MSA, Buyamin S, Ishak MHI, Rahman MKIA, Otuoze AO, Onotu P, Ramli MSA. A review on monitoring and advanced control strategies for precision irrigation. Computers and Electronics in Agriculture 2020; 173:105441. https://doi.org/10.1016/j.compag.2020.105441

7. Abowd GD, Dey AK, Brown PJ, Davies N, Smith M, Steggles P. Towards a Better Understanding of Context and Context-Awareness. In Proceedings of the 1st international symposium on Handheld and Ubiquitous Computing, 1999; HUC '99:304–307, Karlsruhe, Germany. Springer-Verlag London, UK.

8. Acharya S, Pandey A, Mishra SK, Chaube UC. GIS based graphical user interface for irrigation management. Water Supply 2016; 16:1536–51. https://doi.org/10.2166/ws.2016.081

9. Achmakh L, Janati A, Boullayali A, ElHassani L, Bouziane H. Forecasting olive (*Olea europaea* L.) production using aerobiological and meteorological variables in Tétouan (NW Morocco). Aerobiologia 2020; 36:749–59. https://doi.org/10.1007/s10453-020-09665-5

10. Adams SN, Ac-Pangan WO, Rossi L. Effects of Soil Salinity on Citrus Rootstock 'US-942' Physiology and Anatomy. HortScience 2019; 54:787–92. https://doi.org/10.21273/hortsci13868-19

11. Adeboye OB, Osunbitan JA, Adekalu KO, Okunade DA. Evaluation of FAO-56 Penman-Monteith and temperature-based models in estimating reference evapotranspiration using complete and limited data, application to Nigeria. Agricultural Engineering International: CIGR Journal 2009; 9:1–25.

12. Agricultural and Environmental Data Archive (AEDA). (n.d.). Soil water balance. Environmentdata.Org; Freshwater Biological Association. Retrieved January 13, 2022 from http://www.environmentdata.org/archive/vocabpref:18178

13. Ahmadi H, Nasrolahi A, Sharifipur M, Isvand H. Soybean irrigation scheduling by using the temperature difference of the air and canopy cover l. Water and Irrigation Management 2017; 7;121-134. https://www.doi.org/10.22059/jwim.2018.65502

14. Ahumada-Orellana LE, Ortega-Farías S, Searles PS, Retamales JB. Yield and Water Productivity Responses to Irrigation Cut-off Strategies after Fruit Set Using Stem Water Potential Thresholds in a Super-High-Density Olive Orchard. Frontiers in Plant Science 2017; 8. https://doi.org/10.3389/fpls.2017.01280

15. Alamanos A. Simple hydro-economic tools for supporting small water supply agencies on sustainable irrigation water management. Water Supply 2021. https://doi.org/10.2166/ws.2021.318

16. Alexandris S, Kerkides P. New empirical formula for hourly estimations of reference evapotranspiration. Agricultural Water Management 2003; 60:157–80. https://doi.org/10.1016/s0378-3774(02)00172-5

17. Al-Fuqaha A, Guizani M, Mohammadi M, Aledhari M, Ayyash M. Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications. IEEE Communications Surveys and Tutorials 2015; 17:2347–76. https://doi.org/10.1109/comst.2015.2444095

18. Ali M, Khan N, Khan RUA, Khan K, Farooq KRS. 23. Organic manures effect on the bulb production of onion cultivars under semiarid condition. Pure and Applied Biology (PAB) 2018; 7:1161–70. https://mail.thepab.org/index.php/journal/article/view/581

19. Allen RG, Clemmens AJ, Burt CM, Solomon K, O'Halloran T. Prediction accuracy for project wide evapotranspiration using crop coefficients and reference evapotranspiration. Journal of Irrigation and Drainage Engineering 2005; 131:24–36.

20. Allen RG, Pereira LS, Raes D, Smith M. Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56. FAO - Food and Agriculture Organization of the United Nations, Rome. 1998. http://www.fao.org/3/X0490E/x0490e00.htm

21. Allen RG, Pruitt WO. Rational Use of The FAO Blaney-Criddle Formula. Journal of Irrigation and Drainage Engineering 1986; 112:139–55. https://doi.org/10.1061/(asce)0733-9437(1986)112:2(139)

22. Allen RG, Smith M, Perrier A, Pereira LS. An update for the definition of reference evapotranspiration. ICID Journal for Irrigation and Drainage 1994; 43:1-34.

23. Allen RG. A Penman for all seasons. Journal of Irrigation and Drainage Engineering 1986; 112: 348-368.

24. Allen RG. Self-calibrating method for estimating solar radiation from air temperature. Journal of Hydrologic Engineering 1997; 2: 56-67.

25. Alomran AM, Al-Harbi AAR, Wahb-Allah MA, Alwabel MA, Nadeem MEA, Al-Eter A. Management of irrigation water salinity in greenhouse tomato production under calcareous sandy soil and drip irrigation. Journal of Agricultural Science and Technology 2012; 14:939-950.

26. Alrayess H, Ulke A. Evaluation and development of spatial decision support system. European Water 2017; 60.

27. Alvino A, Ferreira MIFR. Refining Irrigation Strategies in Horticultural Production. Horticulturae 2021; 7:29. https://doi.org/10.3390/horticulturae7020029

28. Antoneli V, Mosele AC, Bednarz JA, Pulido-Fernández M, Lozano-Parra J, Keesstra SD, et al. Effects of Applying Liquid Swine Manure on Soil Quality and Yield Production in Tropical Soybean Crops (Paraná, Brazil). Sustainability 2019; 11:3898. https://doi.org/10.3390/su11143898

29. Ara I, Turner L, Harrison MT, Monjardino M, deVoil P, Rodriguez D. Application, adoption and opportunities for improving decision support systems in irrigated agriculture: A review. Agricultural Water Management 2021; 257:107161. https://doi.org/10.1016/j.agwat.2021.107161

30. Archana A, Radha M, Dheebakaran GA, Vanitha G. Assessment and comparison of potential evapotranspiration models for the district of Coimbatore using a statistical modelling approach. The Pharma Innovation Journal 2021; 10:530-539.

31. ASHRAE Handbook. Fundamentals; American Society of Heating Refrigerating and Air-Conditioning Engineers Inc. Atlanta, GA, USA, 1985.

32. Augustin LK, Yagoob AH, Kirui WK, Peiling Y. Optimal irrigation scheduling for summer maize crop: Based on GIS and CROPWAT application in Hetao district; Inner Mongolia autonomous region, China. Journal of Biology, Agriculture and Healthcare 2015; 5:95-102.

33. Autovino D, Rallo G, Provenzano G. Predicting soil and plant water status dynamic in olive orchards under different irrigation systems with Hydrus-2D: Model performance and scenario analysis. Agricultural Water Management 2018; 203:225–35. https://doi.org/10.1016/j.agwat.2018.03.015

34. B.R. Maurya RV, M.L. Dotaniya VSM, M. Jajoria PD. Enhancing Production Potential of Cabbage and Improves Soil Fertility Status of Indo-Gangetic Plain through Application of Bio-organics and Mineral Fertilizer. International Journal of Current Microbiology and Applied Sciences 2017; 6:301–9. https://doi.org/10.20546/ijcmas.2017.603.033

35. Barzee TJ, Edalati A, El-Mashad H, Wang D, Scow K, Zhang R. Digestate Biofertilizers Support Similar or Higher Tomato Yields and Quality Than Mineral Fertilizer in a Subsurface Drip Fertigation System. Frontiers in Sustainable Food Systems 2019; 3. https://doi.org/10.3389/fsufs.2019.00058

36. Behura S, Sahoo S, Pradan N. Plantation of Cymbopogon Pendulus in amended chromite overburden. Journal of Medicinal and Aromatic Plant Sciences 1998; 20:1048-1051.

37. Bendadouche R, Roussey C, De Sousa G, Chanet J, Hou K. Extension of the Semantic Sensor Network Ontology for Wireless Sensor Networks: The Stimulus-WSNnode-Communication Pattern. In the 5^{th} International Workshop on Semantic Sensor Networks in conjunction with the 11^{th} International Semantic Web Conference (ISWC), Boston, United States. 2012; 1–16.

38. Ben-Gal A, Beiersdorf I, Yermiyahu U, Soda N, Presnov E, Zipori I, et al. Response of young bearing olive trees to irrigation-induced salinity. Irrigation Science 2016; 35:99–109. https://doi.org/10.1007/s00271-016-0525-5

39. Berti A, Tardivo G, Chiaudani A, Rech F, Borin M. Assessing reference evapotranspiration by the Hargreaves method in north-eastern Italy. Agricultural Water Management 2014; 140:20–5. https://doi.org/10.1016/j.agwat.2014.03.015

40. Beshir S. Review on Estimation of Crop Water Requirement, Irrigation Frequency and Water Use Efficiency of Cabbage Production. Journal of Geoscience and Environment Protection 2017; 05:59–69. https://doi.org/10.4236/gep.2017.57007

41. Bhite BR, Pawar PS, Bulbule SV. Standardization of Stage Wise Requirement of Nutrients in Sweet Orange. Trends in Biosciences 2017; 10:5644-5647.

42. Bione MAA, Soares TM, Cova AMW, Paz VP da S, Gheyi HR, Rafael MRS, et al. Hydroponic production of 'Biquinho' pepper with brackish water. Agricultural Water Management 2021; 245:106607. https://doi.org/10.1016/j.agwat.2020.106607

43. Blaney HF, Criddle WD. Determining water requirements in irrigated areas from climatological and irrigation data. Natural Resources Conservation Service USDA 1950; 44.

44. Bolton D. The Computation of Equivalent Potential Temperature. Monthly Weather Review 1980; 108:1046–53. https://doi.org/10.1175/1520-0493(1980)108<1046:tcoept>2.0.co;2

45. Boursianis AD, Papadopoulou MS, Diamantoulakis P, Liopa-Tsakalidi A, Barouchas P, Salahas G, et al. Internet of Things (IoT) and Agricultural Unmanned Aerial Vehicles (UAVs)

in smart farming: A comprehensive review. Internet of Things 2020:100187. https://doi.org/10.1016/j.iot.2020.100187

46. Boyd B, Gauci J, Robertson MP, Duy NV, Gupta R, Gucer V, et al. Building Real-time Mobile Solutions with MQTT and IBM MessageSight. IBM Redbooks; 2014.

47. Brakensiek DL, Osborn HB, Rawls WJ. Field manual for research in agricultural hydrology. Journal of Hydrology 1965; 2:274. https://doi.org/10.1016/0022-1694(65)90047-8

48. Brouwer C, Heibloem M. Irrigation Water Management: Irrigation Water Needs. FAO Training manual no. 3. 1986. http://www.fao.org/3/s2022e/s2022e00.htm#Contents

49. Brouwer C, Heibloem M. Irrigation Water Management: Irrigation Water Needs. FAO Training manual no. 3. 1986. http://www.fao.org/3/s2022e/s2022e00.htm#Contents

50. Brown TC, Mahat V, Ramirez JA. Adaptation to future water shortages in the United States caused by population growth and climate change. Earth's Future 2019; 7:219–234. https://doi.org/10.1029/2018EF001091

51. Campbell GS, Campbell CS, Cobos DR, Crawford RB, Rivera L, Chambers C. Defining water potential—What it is. How to use it. Meter Environment. METER Group, Inc. USA. (Accessed January 13, 2022). https://www.metergroup.com/en/meter-environment/measurement-insights/defining-water-potential

52. Capra A, Scicolone B. Irrigation Scheduling Optimisation in Olive Groves. Journal of Experimental Agriculture International 2018; 28:1–19. https://doi.org/10.9734/jeai/2018/44582

53. Cassandra. (n.d.). Retrieved January 13, 2022, from http://cassandra.apache.org/

54. Chaudhari SR, Gawate AB, Chaudhari RS. Effect of multi nutrient on sweet orange. IOSR Journal of VLSI and Signal Processing 2016; 06:32–4. https://doi.org/10.9790/4200-0604013234

55. Chiarelli DD, Passera C, Rosa L, Davis KF, D'Odorico P, Rulli MC. The green and blue crop water requirement WATNEEDS model and its global gridded outputs. Scientific Data 2020; 7. https://doi.org/10.1038/s41597-020-00612-0

56. Chuan L, Zheng H, Sun S, Wang A, Liu J, Zhao T, Zhao J. A Sustainable Way of Fertilizer Recommendation Based on Yield Response and Agronomic Efficiency for Chinese Cabbage. Sustainability 2019; 11:4368. https://doi.org/10.3390/su11164368

57. Climate Change – IPCC 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013; 1535. https://doi.org/10.1017/CBO9781107415324

58. Coolong T, Ribeiro da Silva ALB, Shealey J. Fertilizer Program Impacts Yield and Blossom End Rot in Bell Pepper. HortTechnology 2019; 29:163–9. https://doi.org/10.21273/horttech04249-18

59. Crops statistical year book of the Food and Agriculture Organization (FAO) of the United Nations, Rome – FAOSTAT, 2001. http://www.fao.org/faostat/en/#data/QC

60. D'Odorico P, Davis KF, Rosa L, Carr JA, Chiarelli D, Dell'Angelo J, et al. The Global Food-Energy-Water Nexus. Reviews of Geophysics 2018; 56:456–531. https://doi.org/10.1029/2017rg000591

61. Dashtabi RD, Mirhashemi SH, Jahani M, Jou PH. The Role of Irrigation Management on Wheat Water Productivity (Case Study: Arzooieh City of Kerman). https://dx.doi.org/10.22059/ijswr.2021.320517.668915

62. Dastane NG. Irrigation and Drainage paper 25 – Effective rainfall in irrigated Agriculture. Food and Agriculture Organization of the United Nations Rome, 1978.

63. David L. Tomato and pepper grafting for high tunnel production: effects on yield, compatibility, and plant morphology. Electronic Theses, Dissertations, and Reports. K-State Electronic Theses, Dissertations, and Reports, 2018.

64. De Swaef T, Verbist K, Cornelis W, Steppe K. Tomato sap flow, stem and fruit growth in relation to water availability in rockwool growing medium. Plant and Soil 2011; 350:237–52. https://doi.org/10.1007/s11104-011-0898-4

65. Deryng D, Conway D, Ramankutty N, Price J, Warren R. Global crop yield response to extreme heat stress under multiple climate change futures. Environmental Research Letters 2014; 9:034011. https://doi.org/10.1088/1748-9326/9/3/034011

66. Doorenbos J, Kassam AH. Irrigation and Drainage Paper No. 33 – Yield response to water. Food and Agriculture Organization (FAO) of the United Nations, Rome, 1977. https://www.fao.org/3/i2800e/i2800e04.pdf

67. Doorenbos J, Pruitt W. Irrigation and Drainage Paper 24 – Guidelines for predicting crop water requirements, Food and Agricultural Organisation of the United Nations, 1977.

68. Doorenbos J, Pruitt WO. Irrigation and Drainage Paper No. 24 – Crop water requirements. Food and Agriculture Organization (FAO) of the United Nations, Rome, 1996. http://www.fao.org/3/s8376e/s8376e.pdf

69. Dumas Y. Tomatoes for processing in the 90s: Nutrition and crop fertilization. Acta Horticulturae 1990.; 277:155–166.

70. Elhag A, Ahmed A. Analysis of Irrigation Water Requirements in Gezira Scheme Using Geographic Information Systems: Case Study Block Number 26 (Dolga). Journal of Engineering and Computer Science 2021; 22:1.

71. El-Hamdi Kh, Omar M, Algeat M. Fertilizer Requiremints of Onion Crop. Journal of Soil Sciences and Agricultural Engineering 2016; 7:903–6. https://doi.org/10.21608/jssae.2016.40542

72. Elia A, Conversa G. A decision support system (GesCoN) for managing fertigation in open field vegetable crops. Part I—methodological approach and description of the software. Frontiers in Plant Science 2015; 6:319. https://doi.org/10.3389/fpls.2015.00319

73. Enchalew B, Gebre SL, Rabo M, Hindaye B, Kedir M, Musa Y, Shafi A. Effect of Deficit Irrigation on Water Productivity of Onion (*Allium cepa* L.) under Drip Irrigation. Irrigation and Drainage Systems Engineering 2016; 05. https://doi.org/10.4172/2168-9768.1000172

74. Er-Raki S, Amazirh A, Ayyoub A, Khabba S, Merlin O, Ezzahar J, et al. Integrating thermal surface temperature into Penman-Monteith model for estimating evapotranspiration and crop water stress of orange orchard in semi-arid region. Acta Horticulturae 2018: 89–96. https://doi.org/10.17660/actahortic.2018.1197.12

75. European Environment Agency (EEA). Water resources across Europe — Confronting water scarcity and drought, EEA Report (European Environment Agency, 2009. n.d. http://www.eea.europa.eu/publications/water-resources-across-europe

76. Ewaid SH, Abed SA, Al-Ansari N. Crop Water Requirements and Irrigation Schedules for Some Major Crops in Southern Iraq. Water 2019; 11:756. https://doi.org/10.3390/w11040756

77. Fredericks JW, Labadie JW, Altenhofen JM. Decision Support System for Conjunctive Stream-Aquifer Management. Journal of Water Resources Planning and Management 1998; 124:69–78. https://doi.org/10.1061/(asce)0733-9496(1998)124:2(69)

78. Fuentes C, Enciso J, Nelson S, Anciso J, Setamou M, Elsayed-Farag S. Yield Production and Water Use Efficiency under Furrow and Drip Irrigation Systems for Watermelon in South Texas. Subtropical Agriculture and Environments 2018; 69: 1-7.

79. Gardner WR, Fireman M. Laboratory studies of Evaporation from soil columns in the presence of a Water Table. Soil Science 1958; 85:244–9. https://doi.org/10.1097/00010694-195805000-00002

80. Gavili E, Moosavi AA, Zahedifar M. Integrated effects of cattle manure-derived biochar and soil moisture conditions on soil chemical characteristics and soybean yield. Archives of

Agronomy and Soil Science 2019; 65:1758–74. https://doi.org/10.1080/03650340.2019.1576864

81. Gawali AS, Meshram NA. Scientifically cultivation of lemon grass -a potential aromatic crop. Plant Archives 2019; 19:2860-2864.

82. Gebremariam HL, Welde K, Kahsay KD. Optimizing yield and water use efficiency of furrow-irrigated potato under different depth of irrigation water levels. Sustainable Water Resources Management 2018; 4:1043–9. https://doi.org/10.1007/s40899-018-0238-4

83. Geisseler D, Aegerter BJ, Miyao EM, Turini T, Cahn MD. Nitrogen in soil and subsurface drip-irrigated processing tomato plants (Solanum lycopersicum L.) as affected by fertilization level. Scientia Horticulturae 2020; 261:108999. https://doi.org/10.1016/j.scienta.2019.108999

84. Gentilucci M, Bufalini M, Materazzi M, Barbieri M, Aringoli D, Farabollini P, et al. Calculation of Potential Evapotranspiration and Calibration of the Hargreaves Equation Using Geostatistical Methods over the Last 10 Years in Central Italy. Geosciences 2021; 11:348. https://doi.org/10.3390/geosciences11080348

85. Gentilucci M, Bufalini M, Materazzi M, Barbieri M, Aringoli D, Farabollini P, et al. Calculation of Potential Evapotranspiration and Calibration of the Hargreaves Equation Using Geostatistical Methods over the Last 10 Years in Central Italy. Geosciences 2021; 11:348. https://doi.org/10.3390/geosciences11080348

86. George H. Hargreaves, Zohrab A. Samani. Reference Crop Evapotranspiration from Temperature. Applied Engineering in Agriculture 1985; 1:96–9. https://doi.org/10.13031/2013.26773

87. Giordano R, Passarella G, Uricchio VF, Vurro M. Integrating conflict analysis and consensus reaching in a decision support system for water resource management. Journal of Environmental Management 2007; 84:213–28. https://doi.org/10.1016/j.jenvman.2006.05.006

88. Giwa SO, Muhammad M, Giwa A. Utilizing orange peels for essential oil production. ARPN Journal of Engineering and Applied Sciences 2018; 13:17-27.

89. Goh EH, Ng JL, Huang YF, Yong SLS. Performance of potential evapotranspiration models in Peninsular Malaysia. Journal of Water and Climate Change 2021; 12:3170–86. https://doi.org/10.2166/wcc.2021.018

90. Gourdji SM, Sibley AM, Lobell DB. Global crop exposure to critical high temperatures in the reproductive period: historical trends and future projections. Environmental Research Letters 2013; 8:024041. https://doi.org/10.1088/1748-9326/8/2/024041

91. Gray J. (n.d.). The Transaction Concept: Virtues and Limitations. Appeared in Proceedings of Seventh International Conference on Very Large Databases, Sept. 1981. Tandem Computers Incorporated. Retrieved January 13, 2022, from http://research.microsoft.com/enus/um/people/gray/papers/thetransactionconcept.pdf

92. Guo D, Chen Z, Huang D, Zhang J. Evapotranspiration Model-based Scheduling Strategy for Baby Pakchoi Irrigation in Greenhouse. HortScience 2021; 56:204–9. https://doi.org/10.21273/hortsci15513-20

93. Gupta N, Tiwari A, Tiwari GN. Exergy analysis of building integrated semitransparent photovoltaic thermal (BiSPVT) system. Engineering Science and Technology, an International Journal 2017; 20:41–50. https://doi.org/10.1016/j.jestch.2016.09.013

94. Gururani MA, Venkatesh J, Tran LSP. Regulation of Photosynthesis during Abiotic Stress-Induced Photoinhibition. Molecular Plant 2015; 8:1304–20. https://doi.org/10.1016/j.molp.2015.05.005

95. Hargreaves GH, Allen RG. History and Evaluation of Hargreaves Evapotranspiration Equation. Journal of Irrigation and Drainage Engineering 2003; 129:53–63. https://doi.org/10.1061/(asce)0733-9437(2003)129:1(53)

96. Harizopoulos S, Abadi DJ, Madden S, Stonebraker M. OLTP through the looking glass, and what we found there. Proceedings of the 2008 ACM SIGMOD international conference on Management of data – SIGMOD '08, New York, New York, USA: ACM Press; 2008.

97. Hawkins E, Fricker TE, Challinor AJ, Ferro CAT, Ho CK, Osborne TM. Increasing influence of heat stress on French maize yields from the 1960s to the 2030s. Global Change Biology 2013; 19:937–47. https://doi.org/10.1111/gcb.12069

98. Horrocks RD, Vallentine JF. Water Relations and Irrigation. Harvested Forages, Elsevier; 1999; 225–42.

99. Horsáková J, Krška B. Evaluation of dormancy break in some selected peach (Prunus persica) cultivars. Horticultural Science 2016; 43:181–7. https://doi.org/10.17221/154/2014-hortsci

100. Houérou HN. Bioclimatology and Biogeography of Africa. Springer Science & Business Media; 2009.

101. Htoo T. Macro Analysis of Climate Change and Agricultural Production in Myanmar. IntechOpen 2021. https://www.intechopen.com/chapters/77614

102. Hugron S, Bussières J, Rochefort L. Tree plantations within the context of ecological restoration of peatlands: practical guide. Laval, Québec, Canada: Peatland Ecology Research Group (PERG), 2013.

103. IBM Redbooks, 2014. Retrieved January 13, 2022. https://books.google.com.br/books?id=R3tNBQAAQBAJ

104. India Agro Net. 2018. Retrieved January 13, 2022. https://www.indiaagronet.com/indiaagronet/water_management/water_3.htm

105. Islam Ms, Saif H, Islam Mr, Naher Q, Khan A. Soil salinity management for increasing potato yield in the coastal area of southern Bangladesh. Bangladesh Journal of Agricultural Research 2018; 43:655–68. https://doi.org/10.3329/bjar.v43i4.39164

106. Jahanzad E, Barker AV, Hashemi M, Sadeghpour A, Eaton T. Forage Radish and Winter Pea Cover Crops Outperformed Rye in a Potato Cropping System. Agronomy Journal 2017; 109:646–53. https://doi.org/10.2134/agronj2016.06.0342

107. Jones FE. Evaporation of water: with emphasis on applications and measurements, Lewis Publishers, Inc., Chelsea, Michigan, 1992.

108. Jones H. Radiation. In Plants and Microclimate: A Quantitative Approach to Environmental Plant Physiology 2013; 9-46. Cambridge: Cambridge University Press. https://www.doi.org/10.1017/CBO9780511845727.003

109. Kang F, Wang Z, Xiong H, Li Y, Wang Y, Fan Z, Zhao H, Kuang D, Chen Z, Wang, J, He X, Chen X, Shi X, Zhang Y. Estimation of Watermelon Nutrient Requirements Based on the QUEFTS Model. Agronomy 2020; 10:1776. https://doi.org/10.3390/agronomy10111776

110. Karthe D. Environmental changes in central and east Asian drylands and their effects on large central and east Asian lakes and their effects on major river-lake systems. Quaternary International 2018; 475:91-100.

111. Katerji N, Mastrorilli M, Cherni HE. Effects of corn deficit irrigation and soil properties on water use efficiency. A 25-year analysis of a Mediterranean environment using the STICS model. European Journal of Agronomy 2010; 32:177-185. https://doi.org/10.1016/j.eja.2009.11.001

112. Kaufmann RK, Cutler JC. Environmental Science. McGraw-Hill. 2008; 318–319.

113. Keck A. Evapotranspiration: Watching over water use. National Aeronautics and Space Administration (NASA), 2021. https://www.nasa.gov/feature/evapotranspiration-watching-over-water-use

114. Keswani B, Mohapatra AG, Keswani P, Khanna A, Gupta D, Rodrigues J. Improving weather dependent zone-specific irrigation control scheme in IoT and big data enabled self-driven precision agriculture mechanism. Enterprise Information Systems 2020; 14:1494–515. https://doi.org/10.1080/17517575.2020.1713406

115. Khadra R, Lamaddalena N. Development of a Decision Support System for Irrigation Systems Analysis. Water Resources Management 2010; 24:3279–97. https://doi.org/10.1007/s11269-010-9606-z

116. Khan MZ, Ahmed H, Ahmed S, Khan A, Khan RU, Hussain F, et al. Formulation of humic substances coated fertilizer and its use to enhance K fertilizer use efficiency for tomato under greenhouse conditions. Journal of Plant Nutrition 2019; 42:626–33. https://doi.org/10.1080/01904167.2019.1568462

117. Khan WA, Ul Rahman J, Mohammed M, AlHussain ZA, Elbashir MK. Topological Sustainability of Crop Water Requirements and Irrigation Scheduling of Some Main Crops Based on the Penman-Monteith Method. Journal of Chemistry 2021; 12. https://doi.org/10.1155/2021/8552547

118. Klerkx L, Begemann S. Supporting food systems transformation: The what, why, who, where and how of mission-oriented agricultural innovation systems. Agricultural Systems 2020; 184:102901. https://doi.org/10.1016/j.agsy.2020.102901

119. Klerkx L, Jakku E, Labarthe P. A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. NJAS - Wageningen Journal of Life Sciences 2019; 90–91:100315. https://doi.org/10.1016/j.njas.2019.100315

120. Knezevic M, Zivotic L, Perovic V, Topalovic A, Todorovic M. Impact of climate change on olive growth suitability, Water demands and yield in Montenegro. Italian Journal of Agrometeorology 2017; 2:39-52.

121. Kruger M, Sigdel S, Gasch C, DeSutter T, Harmon J, Chatterjee A. Soil carbon dioxide efflux from amended saline and thermally desorbed oil-contaminated subsoil. Agrosystems, Geosciences and Environment 2020; 3. https://doi.org/10.1002/agg2.20100

122. Kumar S, Attri SD, Soni AK, Vishnoi L, Singh KK, Sharma G, Tripathi JN. Satellite derived crop coefficient and crop water stress for soybean in semi-arid region of India. Journal of Agrometeorology 2019; 21:144-151.

123. Lampkin V, Leong WT, Olivera L, Rawat S, Subrahmanyam N, Xiang R, et al. Building Smarter Planet Solutions with MQTT and IBM WebSphere MQ Telemetry. IBM Redbooks; 2012.

124. Land and Water. Food and Agriculture Organization (FAO) of the United Nations. n.d. (accessed January 17, 2022). https://www.fao.org/land-water/home/en/

125. Lesk C, Rowhani P, Ramankutty N. Influence of extreme weather disasters on global crop production. Nature 2016; 529:84–7. https://doi.org/10.1038/nature16467

126. Li H, Lu X, Wei Z, Zhu S, Wei N, Zhang Shupeng, et al. New Representation of Plant Hydraulics Improves the Estimates of Transpiration in Land Surface Model. Forests 2021; 12:722. https://doi.org/10.3390/f12060722

127. Liu H, Duan A, LI F, Sun J, Wang Y, Sun C. Drip Irrigation Scheduling for Tomato Grown in Solar Greenhouse Based on Pan Evaporation in North China Plain. Journal of Integrative Agriculture 2013; 12:520–31. https://doi.org/10.1016/s2095-3119(13)60253-1

128. Liu J, Hu T, Feng P, Wang L, Yang S. Tomato yield and water use efficiency change with various soil moisture and potassium levels during different growth stages. PLOS ONE 2019; 14:e0213643. https://doi.org/10.1371/journal.pone.0213643

129. Liu Z, Jiao X, Zhu C, Katul GG, Ma J, Guo W. Micro-climatic and crop responses to micro-sprinkler irrigation. Agricultural Water Management 2021; 243:106498. https://doi.org/10.1016/j.agwat.2020.106498

130. Lobell DB, Roberts MJ, Schlenker W, Braun N, Little BB, Rejesus RM, et al. Greater Sensitivity to Drought Accompanies Maize Yield Increase in the U.S. Midwest. Science 2014; 344:516–9. https://doi.org/10.1126/science.1251423

131. Locke D. MQTT V3.1 Protocol Specification. n.d. https://public.dhe.ibm.com/software/dw/webservices/ws-mqtt/mqtt-v3r1.html (accessed January 13, 2022).

132. López-Urrea R, Martín de Santa Olalla F, Fabeiro C, Moratalla A. Testing evapotranspiration equations using lysimeter observations in a semiarid climate. Agricultural Water Management 2006; 85:15–26. https://doi.org/10.1016/j.agwat.2006.03.014

133. Lovelli S, Potenza G, Castronuovo D, Perniola M, Candido V. Yield, quality and water use efficiency of processing tomatoes produced under different irrigation regimes in Mediterranean environment. Italian Journal of Agronomy 2016; 11. https://doi.org/10.4081/ija.2016.795

134. Ma Y, Xu A, Cheng Z-M (Max). Effects of light emitting diode lights on plant growth, development and traits a meta-analysis. Horticultural Plant Journal 2021; 7:552–64. https://doi.org/10.1016/j.hpj.2020.05.007

135. Machler MA, Iqbal M. A modification of the ASHRAE clear sky irradiation model. ASHRAE Transactions 1967; 91:106–115.

136. Mahadevan R. Productivity growth in Indian agriculture: The role of globalization and economic reform. Asia-Pacific Development Journal 2003; 10:57–72. https://doi.org/10.18356/5728288b-en

137. Malash N, Ali F, Fatahalla MA, Khatab E, Hatem M, Tawfic S. Response of tomato to irrigation with saline water applied by different irrigation methods and water management strategies. International Journal of Plant Production 2012 2:101-116. https://www.doi.org/10.22069/ijpp.2012.603

138. Mason B, Rufí-Salís M, Parada F, Gabarrell X, Gruden, C. Intelligent urban irrigation systems: Saving water and maintaining crop yields. Agricultural Water Management 226 2019. https://doi.org/10.1016/j.agwat.2019.105812

139. Maxwell RM, Condon LE. Connections between groundwater flow and transpiration partitioning. Science 2016; 353:377–80. https://doi.org/10.1126/science.aaf7891

140. McGrath M. (n.g.). Warming world 'devastating' for frozen peatlands. BBC News. Retrieved January 13, 2022.

141. Ministry of Water Resources of China. 2016 China Water Resources Bulletin; China Water Power Press: Beijing, China, 2017.

142. Mirzajani MR, Majidian M, Mohsenabadi GR. Evaluating the Effect of Integrated Nutrition on Quantitative Yield and Essential Oil Percentage of Lemon Balm (*Melissa officinalis*). Journal of Plant Productions 2019 42:469-482. https://www.doi.org/10.22055/PPD.2019.25695.1594

143. Miyasaka SC, Hamasaki RT. Promising Olive Cultivars for Oil Production in Hawaii. HortTechnology 2016; 26:497–506. https://doi.org/10.21273/horttech.26.4.497

144. Monte JA, Carvalho DF de, Medici LO, Silva LDB da, Pimentel C. Growth analysis and yield of tomato crop under different irrigation depths. Revista Brasileira de Engenharia Agrícola e Ambiental 2013; 17:926–31. https://doi.org/10.1590/s1415-43662013000900003

145. Morgan KT, Zotarelli L, Dukes MD. Use of Irrigation Technologies for Citrus Trees in Florida. HortTechnology 2010; 20:74–81. https://doi.org/10.21273/horttech.20.1.74

146. Morgan KT, Zotarelli L, Dukes MD. Use of Irrigation Technologies for Citrus Trees in Florida. HortTechnology 2010; 20:74–81. https://doi.org/10.21273/horttech.20.1.74

147. Mubarak I, Hamdan A. Onion Crop Response to Regulated Deficit Irrigation under Mulching in Dry Mediterranean Region. Journal of Horticultural Research 2018; 26:87–94. https://doi.org/10.2478/johr-2018-0010

148. Müller C, Bondeau A, Popp A, Waha K, Fader M. WRD 2010: development and climate change World Development Report, 2010; 1–12.

149. Murchie EH, Niyogi KK. Manipulation of Photoprotection to Improve Plant Photosynthesis. Plant Physiology 2010; 155:86–92. https://doi.org/10.1104/pp.110.168831

150. Murugesan S, Scheibel T. Copolymer/Clay Nanocomposites for Biomedical Applications. Advanced Functional Materials 2020; 30:1908101. https://doi.org/10.1002/adfm.201908101

151. Nassah H, Er-Raki S, Khabba S, Fakir Y, Raibi F, Merlin O, et al. Evaluation and analysis of deep percolation losses of drip irrigated citrus crops under non-saline and saline conditions in a semi-arid area. Biosystems Engineering 2018; 165:10–24. https://doi.org/10.1016/j.biosystemseng.2017.10.017

152. Nelson G, Rosegrant M, Palazzo A, Gray I, Ingersoll C, Robertson R, Tokgoz S, Zhu T, Sulser T, Ringler C, Msangi S, You L. Food security, farming, and Climate change to 2050: Scenarios, results, policy options. International Food Policy Research Institute, Washington, D.C., USA, 2010.

153. Nijegorodov N. Improved ashrae model to predict hourly and daily solar radiation components in Botswana, Namibia, and Zimbabwe. WREC 1996; 9:1270–1273.

154. NoSQL Databases, a list. (n.d.). Retrieved January 13, 2022, from http://nosql-database.org/

155. Paredes P, Fontes JC, Azevedo EB, Pereira LS. Daily reference crop evapotranspiration in the humid environments of Azores islands using reduced data sets: accuracy of FAO-PM temperature and Hargreaves-Samani methods. Theoretical and Applied Climatology 2018; 134:595–611. https://doi.org/10.1007/s00704-017-2295-2

156. Parishwad GV, Bhardwaj RK, Nema VK. Estimation of hourly solar radiation for India. Renewable Energy 1997; 12:303–13. https://doi.org/10.1016/s0960-1481(97)00039-6

157. Paz JO, Fraisse CW, Hatch LU, Garcia y Garcia A, Guerra LC, Uryasev O, et al. Development of an ENSO-based irrigation decision support tool for peanut production in the southeastern US. Computers and Electronics in Agriculture 2007; 55:28–35. https://doi.org/10.1016/j.compag.2006.11.003

158. Pereira AS, Santos GR dos, Sarmento RA, Galdino TV da S, Lima CH de O, Picanço MC. Key factors affecting watermelon yield loss in different growing seasons. Scientia Horticulturae 2017; 218:205–12. https://doi.org/10.1016/j.scienta.2017.02.030

159. Perniola M. Il Clima e le Piante, Agrometeorlogia. Agrometeorologia 2021; 4(2).

160. Pinheiro DT, Delazari F, Nick C, Mattiello EM, Dias DCF dos S. Emergence and vegetative development of melon in function of the soil salinity. 2019; 13:458–64. https://doi.org/10.21475/ajcs.19.13.03.p1551

161. Porter JR, Thorburn PJ, Brown HE, Teixeira EI, Moot DJ, Mills A, et al. Deconstructing agronomic resource use efficiencies to increase food production. Italian Journal of Agronomy 2021; 16. https://doi.org/10.4081/ija.2021.1694

162. Puglisi, Nicolosi, Vanella, Piero, Stagno, Saitta, et al. Physiological and Biochemical Responses of Orange Trees to Different Deficit Irrigation Regimes. Plants 2019; 8:423. https://doi.org/10.3390/plants8100423

163. Qin W, Heinen M, Assinck FBT, Oenema O. Exploring optimal fertigation strategies for orange production, using soil–crop modelling. Agriculture, Ecosystems & Environment 2016; 223:31–40. https://doi.org/10.1016/j.agee.2016.02.025

164. Rajasekaram V, Nandalal K. Decision support system for reservoir water management conflict resolution. Journal of Water Resources Planning and Management 2005; 131:410–419. https://doi.org/10.1061/(ASCE)0733-9496(2005)131:6(410)

165. Rameshwaran P, Tepe A, Yazar A, Ragab R. Effects of drip-irrigation regimes with saline water on pepper productivity and soil salinity under greenhouse conditions. Scientia Horticulturae 2016; 199:114–23. https://doi.org/10.1016/j.scienta.2015.12.007

166. Rao M, Fan G, Thomas J, Cherian G, Chudiwale V, Awawdeh M. A web-based GIS Decision Support System for managing and planning USDA's Conservation Reserve Program (CRP). Environmental Modelling & Software 2007; 22:1270–80. https://doi.org/10.1016/j.envsoft.2006.08.003

167. Redis. (n.d.). Retrieved January 13, 2022, from http://redis.io/

168. Regents of the University of California. Solution center for nutrient management. University of California, Division of Agriculture and Natural Resources, 2020. https://ucanr.edu/sites/Nutrient_Management_Solutions/

169. Ribeiro H, Abreu I, Cunha M. Olive crop-yield forecasting based on airborne pollen in a region where the olive groves acreage and crop system changed drastically. Aerobiologia 2017; 33:473–80. https://doi.org/10.1007/s10453-017-9483-5

170. Rinaldi M, Ventrella D, Gagliano C. Comparison of nitrogen and irrigation strategies in tomato using CROPGRO model. A case study from Southern Italy. Agricultural Water Management 2007; 87:91–105. https://doi.org/10.1016/j.agwat.2006.06.006

171. Rodriguez-Dominguez CM, Brodribb TJ. Declining root water transport drives stomatal closure in olive under moderate water stress. New Phytologist 2019; 225:126–34. https://doi.org/10.1111/nph.16177

172. Romero-Aranda R, Soria T, Cuartero J. Tomato plant-water uptake and plant-water relationships under saline growth conditions. Plant Science 2001; 160:265–72. https://doi.org/10.1016/s0168-9452(00)00388-5

173. Ropokis A, Ntatsi G, Kittas C, Katsoulas N, Savvas D. Effects of Temperature and Grafting on Yield, Nutrient Uptake, and Water Use Efficiency of a Hydroponic Sweet Pepper Crop. Agronomy 2019; 9:110. https://doi.org/10.3390/agronomy9020110

174. Rose DC, Chilvers J. Agriculture 4.0: Broadening Responsible Innovation in an Era of Smart Farming. Frontiers in Sustainable Food Systems 2018; 2. https://doi.org/10.3389/fsufs.2018.00087

175. Rose DC, Wheeler R, Winter M, Lobley M, Chivers C-A. Agriculture 4.0: Making it work for people, production, and the planet. Land Use Policy 2021; 100:104933. https://doi.org/10.1016/j.landusepol.2020.104933

176. Sabouri Z, Fereydouni N, Akbari A, Hosseini HA, Hashemzadeh A, Amiri MS, et al. Plant-based synthesis of NiO nanoparticles using salvia macrosiphon Boiss extract and examination of their water treatment. Rare Metals 2019; 39:1134–44. https://doi.org/10.1007/s12598-019-01333-z

177. Sahin U, Ekinci M, Ors S, Turan M, Yildiz S, Yildirim E. Effects of individual and combined effects of salinity and drought on physiological, nutritional and biochemical properties of cabbage (*Brassica oleracea var. capitata*). Scientia Horticulturae 2018; 240:196–204. https://doi.org/10.1016/j.scienta.2018.06.016

178. Said MF, Mohammed AGH, Abdall EMMS. Adoption of an intelligent irrigation scheduling technique and its effect on water use efficiency for tomato crops in arid regions. Australian Journal of Crop Science 2013; 7:305-313. https://search.informit.com.au/documentSummary;dn=260957318485967;res=IELHSS

179. Samani Z. Discussion of "History and Evaluation of Hargreaves Evapotranspiration Equation"by George H. Hargreaves and Richard G. Allen. Journal of Irrigation and Drainage Engineering 2004; 130:447–8. https://doi.org/10.1061/(asce)0733-9437(2004)130:5(447.2)

180. Sarafi E, Siomos A, Tsouvaltzis P, Therios I, Chatzissavvidis C. The influence of Boron on pepper plants nutritional status and nutrient efficiency. Journal of Soil Science and Plant Nutrition 2018; 18. https://doi.org/10.4067/s0718-95162018005001903

181. Sary D, Elsokkary I. Effect of irrigation water regime in presence of organic or biological fertilizer on olive trees. Egyptian Journal of Soil Science 2019; 59: 67-48. https://doi.org/10.21608/ejss.2019.6740.1245

182. Schwarz D, Kuchenbuch R. Water uptake by Tomato plants grown in closed Hydroponic Systems dependent on the EC-level. Acta Horticulturae 1998; 323–8. https://doi.org/10.17660/actahortic.1998.458.41

183. Seifi A, Soroush F. Pan evaporation estimation and derivation of explicit optimized equations by novel hybrid meta-heuristic ANN based methods in different climates of Iran. Computers and Electronics in Agriculture 2020; 173:105418. https://doi.org/10.1016/j.compag.2020.105418

184. Shaffer MJ, Brodahl MK. Rule-based management for simulation in agricultural decision support systems. Computers and Electronics in Agriculture 1998; 21: 135-152. https://doi.org/10.1016/S0168-1699(98)00031-3

185. Shahidian S, Serralheiro R, Serrano J, Teixeira J, Haie N, Santos F. Hargreaves and Other Reduced-Set Methods for Calculating Evapotranspiration. In Evapotranspiration–Remote Sensing and Modeling; IntechOpen Limited: London, UK, 2012; 59–80.

186. Shahzad F, Chun C, Schumann A, Vashisth T. Nutrient Uptake in Huanglongbing-affected Sweet Orange: Transcriptomic and Physiological Analysis. Journal of the American Society for Horticultural Science 2020; 145:349–62. https://doi.org/10.21273/jashs04929-20

187. Sharma, Kannan, Cook, Pokhrel, McKenzie. Analysis of the Effects of High Precipitation in Texas on Rainfed Sorghum Yields. Water 2019; 11:1920. https://doi.org/10.3390/w11091920

188. Shen Y, Sui P, Huang J, Wang D, Whalen JK, Chen Y. Global warming potential from maize and maize-soybean as affected by nitrogen fertilizer and cropping practices in the North China Plain. Field Crops Research 2018; 225:117–27. https://doi.org/10.1016/j.fcr.2018.06.007

189. Shinde MG, Pawar DD, Kale KD, Dingre SK. Performance of cabbage at different irrigation levels under drip and microsprinkler irrigation systems. Irrigation and Drainage 2020; 70:581–92. https://doi.org/10.1002/ird.2557

190. Singh N, Singh AN. Odysseys of agriculture sensors: Current challenges and forthcoming prospects. Computers and Electronics in Agriculture 2020; 171:105328. https://doi.org/10.1016/j.compag.2020.105328

191. Soil Survey Staff. Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys. 2nd edition. Natural Resources Conservation Service. U.S. Department of Agriculture Handbook 436, 1999.

192. Soratto RP, Job ALG, Fernandes AM, Assunção NS, Fernandes FM. Biomass Accumulation and Nutritional Requirements of Potato as Affected by Potassium Supply. Journal of Soil Science and Plant Nutrition 2020; 20:1051–66. https://doi.org/10.1007/s42729-020-00192-3

193. Stanford-Clark A, Truong HL. MQTT for sensor networks (MQTT-sn) protocol specification, 2013. Retrieved January 13, 2022. https://www.oasis-open.org/committees/download.php/66091/MQTT-SN_spec_v1.2.pdf

194. Statistics Canada (n.d.). Agricultural Water Survey; Government of Canada, 2018. Retrieved October 20, 2021, from https://www150.statcan.gc.ca/n1/daily-quotidien/190912/dq190912d-eng.htm

195. Steduto P, Hsiao TC, Fereres E, Raes D. Irrigation and drainage paper 66 – Crop yield response to Water. Food and Agriculture Organization (FAO) of the United Nations, Rome, 2012. http://www.fao.org/3/i2800e/i2800e.pdf

196. Stonebraker M. SQL databases v. NoSQL databases. Communications of the ACM Communication 2010; 53: 10.

197. Sun J, De Sousa G, Roussey C, Chanet JP, Pinet F, Hou KM. Intelligent Flood Adaptive Context-aware System: How Wireless Sensors Adapt their Configuration based on Environmental Phenomenon Events. Sensors and Transducers 2016; 206:68–81. https://hal.inrae.fr/hal-02605241

198. Suryadi E, Kendarto DR, Sistanto BA, Ruswandi D. A Study of Crop Water Needs and Land Suitability in the Monoculture System and Plant Intercropping in Arjasari. International Journal on Advanced Science, Engineering and Information Technology 2018; 8:554. https://doi.org/10.18517/ijaseit.8.2.4943

199. Takács S, Pék Z, Csányi D, Daood HG, Szuvandzsiev P, Palotás G, et al. Influence of Water Stress Levels on the Yield and Lycopene Content of Tomato. Water 2020; 12:2165. https://doi.org/10.3390/w12082165

200. Tegos A, Malamos N, Efstratiadis A, Tsoukalas I, Karanasios A, Koutsoyiannis D. Parametric Modelling of Potential Evapotranspiration: A Global Survey. Water 2017; 9:795. https://doi.org/10.3390/w9100795

201. Tegos A, Malamos N, Koutsoyiannis D. A parsimonious regional parametric evapotranspiration model based on a simplification of the Penman–Monteith formula. Journal of Hydrology 2015; 524:708–17. https://doi.org/10.1016/j.jhydrol.2015.03.024

202. Thevs N, Aliev K, Lleshi R. Water productivity of tree wind break agroforestry systems in irrigated agriculture – An example from Ferghana Valley, Kyrgyzstan. Trees, Forests and People 2021; 4:100085. https://doi.org/10.1016/j.tfp.2021.100085

203. Thornthwaite CW. An Approach toward a Rational Classification of Climate. Geographical Review 1948; 38:55. https://doi.org/10.2307/210739

204. Trabelsi L, Gargouri K, Ben Hassena A, Mbadra C, Ghrab M, Ncube B, et al. Impact of drought and salinity on olive water status and physiological performance in an arid climate. Agricultural Water Management 2019; 213:749–59. https://doi.org/10.1016/j.agwat.2018.11.025

205. Valecce G, Strazzella S, Radesca A, Grieco LA. Solarfertigation: Internet of Things architecture for Smart Agriculture. 2019. https://telematics.poliba.it/publications/2019/ValecceCIOT2019.pdf

206. Vandandorj S, Munkhjargal E, Boldgiv B, Gantsetseg B. Changes in event number and duration of rain types over Mongolia from 1981 to 2014. Environmental Earth Sciences 2017; 76. https://doi.org/10.1007/s12665-016-6380-0

207. Visconti P, de Fazio R, Primiceri P, Cafagna D, Strazzella S, Giannoccaro NI. A Solar-Powered Fertigation System Based on Low-Cost Wireless Sensor Network Remotely Controlled by Farmer for Irrigation Cycles and Crops Growth Optimization - International Journal of Electronics and Telecommunications - PAS Journals Repository. International Journal of Electronics and Telecommunications 2020: 59-68-59–68. https://doi.org/https://journals.pan.pl/publication/130266

208. Wada Y, Wisser D, Eisner S, Flörke M, Gerten D, Haddeland I, et al. Multimodel projections and uncertainties of irrigation water demand under climate change. Geophysical Research Letters 2013; 40:4626–32. https://doi.org/10.1002/grl.50686

209. Wallace JS. Increasing agricultural water use efficiency to meet future food production. Agriculture, Ecosystems and Environment 2000; 82:105–19. https://doi.org/10.1016/s0167-8809(00)00220-6

210. Waller P, Yitayew M. Crop evapotranspiration. In Irrigation and Drainage Engineering, Springer, Switzerland, 2016; 89–104.

211. Wang W, Wan Q, Li Y, Xu W, Yu X. Uptake, translocation and subcellular distribution of pesticides in Chinese cabbage (Brassica rapa var. chinensis). Ecotoxicology and Environmental Safety 2019; 183:109488. https://doi.org/10.1016/j.ecoenv.2019.109488

212. Wang Z, Wu P, Zhao X, Cao X, Gao Y. GANN models for reference evapotranspiration estimation developed with weather data from different climatic regions. Theoretical and Applied Climatology 2013; 116:481–9. https://doi.org/10.1007/s00704-013-0967-0

213. Warner J, Zhang TQ, Hao X. Effects of nitrogen fertilization on fruit yield and quality of processing tomatoes. Canadian Journal of Plant Science 2004; 84:865–71. https://doi.org/10.4141/p03-099

214. Winnicki T, Bogucka B. Evaluation of different potato fertilization regimes on starch yield – Production and economic aspects. Polish Journal of Natural Sciences 2017; 32:637–648. http://www.uwm.edu.pl/polish-journal/sites/default/files/issues/articles/winnicki_and_bogucka_2017.pdf

215. Wu J, Zha J, Zhao D, Yang Q. Changes in terrestrial near-surface wind speed and their possible causes: an overview. Climate Dynamics 2017; 51:2039–78. https://doi.org/10.1007/s00382-017-3997-y

216. Wu Z, Cui N, Zhu B, Zhao L, Wang X, Hu X, et al. Improved Hargreaves Model Based on Multiple Intelligent Optimization Algorithms to Estimate Reference Crop Evapotranspiration in Humid Areas of Southwest China. Atmosphere 2020; 12:15. https://doi.org/10.3390/atmos12010015

217. Xin P, Li B, Zhang H, Hu J. Optimization and control of the light environment for greenhouse crop production. Scientific Reports 2019; 9. https://doi.org/10.1038/s41598-019-44980-z

218. Xu CY, Singh VP. Cross Comparison of Empirical Equations for Calculating Potential Evapotranspiration with Data from Switzerland. Water Resources Management 2002; 16: 197–219. https://doi.org/10.1023/A:1020282515975

219. Yang L, Qu H, Zhang Y, Li F. Effects of partial root-zone irrigation on physiology, fruit yield and quality and water use efficiency of tomato under different calcium levels. Agricultural Water Management 2012; 104:89–94. https://doi.org/10.1016/j.agwat.2011.12.001

220. Yohannes DF, Ritsema CJ, Habtu S, Van Dam JC, Froebrich J. Effect of cyclic irrigation using moderately saline and non-saline water on onion (Allium cepaL.) yield and soil salinization in semi-arid areas of Northern Ethiopia*. Irrigation and Drainage 2020; 69:1082–94. https://doi.org/10.1002/ird.2493

221. Zabel F, Müller C, Elliott J, Minoli S, Jägermeyr J, Schneider JM, et al. Large potential for crop production adaptation depends on available future varieties. Global Change Biology 2021; 27:3870–82. https://doi.org/10.1111/gcb.15649

222. Zaghloul A, Moursi E-S. Effect of Irrigation Scheduling under some Biostimulants Foliar Application for Navel Orange Trees on some Water Relations, Productivity, Fruit Quality and Storability in the North Nile Delta Region. Alexandria Science Exchange Journal 2017; 38:671–86. https://doi.org/10.21608/asejaiqjsae.2017.4103

223. Zambon I, Cecchini M, Egidi G, Saporito MG, Colantoni A. Revolution 4.0: Industry vs. Agriculture in a Future Development for SMEs. Processes 2019; 7:36. https://doi.org/10.3390/pr7010036

224. Zhang Y, Zhao C, Lin S, Guo W, Wen C, Long J. Irrigation Method and Verification of Strawberry Based on Penman-Monteith Model and Path Ranking Algorithm. Smart Agriculture 2021; 3:116-128

225. Zhao C, Piao S, Huang Y, Wang X, Ciais P, Huang M, et al. Field warming experiments shed light on the wheat yield response to temperature in China. Nature Communications 2016; 7. https://doi.org/10.1038/ncomms13530

226. Zucco MA, Walters SA, Chong S-K, Klubek BP, Masabni JG. Effect of soil type and vermicompost applications on tomato growth. International Journal of Recycling of Organic Waste in Agriculture 2015; 4:135–41. https://doi.org/10.1007/s40093-015-0093-3

La borsa di dottorato è stata cofinanziata con risorse del
Programma Operativo Nazionale Ricerca e Innovazione 2014-2020 (CCI 2014IT16M2OP005),
Fondo Sociale Europeo, Azione I.1 "Dottorati Innovativi con caratterizzazione Industriale"

UNIONE EUROPEA
Fondo Sociale Europeo

Ministero dell'Università
e della Ricerca

PON
RICERCA
E INNOVAZIONE
2014 - 2020