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Durum wheat irrigation research trends on essential scientific indicators: a bibliometric analysis

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Abstract. Nowadays irrigation of durum wheat represents a key point to provide food security in a context of climate change. Although this topic has caught on particular attention from the global scientific community, many issues and aspects remains understudied. To fill the knowledge gap and collate present evidences, this analysis used a combined bibliometric and thematic approach to synthesize the peer-review literature from SCOPUS main collection, covering the period 1977-2023, resulting in including 332 documents. The main findings of this work are as follows:
(1) Spain and Tunisia hosts the most productive institutions in this field;
(2) the journal Agricultural Water Management emerged as the most prolific, with the largest number of articles and citations;
(3) a wide range of topics and approaches on durum wheat irrigation has been identified, with particular emphasis on controlled water deficit and remote sensing driven management;
(4) the mapping of bibliographic data coupling with co-occurrence map remains a poorly examined area of study.
The results suggest the need of strengthened institutional partnerships and synergize the research on durum wheat irrigation, particularly in the most vulnerable areas where climate change are acting heavily. Future studies should aim to contribute to the understanding of the impacts of climate change through innovative techniques in order to improve our understanding of the durum wheat water needs and their application in crop management, while ensuring ongoing updates to the existing collection of knowledge to face future challenges.

Keywords: bibliographic coupling, co-authorship and citation networks, durum wheat, durum wheat irrigation, PRISMA protocol, Scopus.

1. INTRODUCTION

Durum wheat (*Triticum turgidum* subsp. *durum* (Desf.) Husnot) is the tenth most cultivated cereal in the world (Ayed et al., 2021), with about 13.7

million hectares cultivated and a production of 34.3 million tons (2018-2022 average) (International Grains Council (IGC)), with wide variations from 30 to 39 million tons caused mainly by abiotic factors (drought, high temperatures, low temperatures or pre-budding) and biotic stress (fungal and viral diseases, weeds or harmful insects) (Blanco, 2024).

Durum wheat is an important food source with a significant role in the human diet, providing carbohydrates, proteins, B vitamins, minerals, and energy (Onipe et al., 2015). Worldwide it is mainly used to produce dry pasta and other staple foods such as couscous and bulgur, the latter in particular in North Africa and the Middle East (Troccoli et al., 2000).

The main concern in the regions of durum wheat cultivation, characterized by arid and semi-arid climates, is the potential water deficit in rainfed conditions and the scares availability of freshwater, therefore there is the need to optimize its use (Oweis T. et al., 1999). In fact, water is one of the main factors limiting wheat yield and protein quality and quantity (Flagella et al., 2010). Drought periods usually coincide with the most sensitive growth phases of the crop. The water stress from the anthesis to the ripening, especially if accompanied by high temperatures, accelerates the leaf senescence, reduces the duration and the speed of the grain-filling, as well as the duration of the phase of translocation of carbohydrate reserves in the caryopsis (Oweis et al., 2000), which reduces the average weight of caryopsis (Acevedo et al., 2002). Furthermore, the water stress around the anthesis can lead to a yield loss due to the reduction of the number of spikes and spikelet and for the fertility of those produced (Giunta et al., 1993). The availability of water also influences nitrogen management in agriculture. In fact, an adequate water supply increases the efficiency of nitrogen use (NUE), improving the assimilation and translocation of N in the caryopses (Wang et al., 2015), with significant effects on quality. Nitrogen and irrigation management are crucial in the production of irrigated durum wheat with high protein content in arid and semi-arid regions (Mon et al., 2016).

The obtaining of high yields and high protein content in durum wheat is also limited by the ongoing climate change, which is intensifying and extending dryness with further reduction of precipitation (IPCC, 2014), more frequent exposure to high temperatures and change in precipitation regimes (Fahad et al., 2017). In addition, to meet the food demand of a projected global population of about 10 billion people by 2050, it is necessary to increase food production compared to the current level (Neupane et al., 2022).

In many growing areas, durum wheat is mainly cultivated in rainfed conditions (Bassi et al., 2017). However, irrigation is an important agronomic practice to meet the demand for grain production (Meena et al., 2019).

The improvement of water use efficiency (WUE) could be achieved through different strategies, some of which, still today, are under investigation such as the selection of genotypes with high photosynthetic capacity and low stomatal conductance (Van den Boogaard et al., 1997; Ashraf & Bashir, 2003; Morgan & LeCain, 1991; Condon et al., 2002) and sustainable agronomic practices such as the adoption of regulated water deficit strategies, the application of biostimulants, non-conventional water resources, etc (Mohammadi, 2024; Ben-Jabeur et al., 2022; Werfelli et al., 2021).

The bibliometric analysis adopted in this study was first introduced by Pritchard (Pritchard, 1969), but its diffusion is more recent (Donthu et al., 2021). It is based on the identification of the body of literature, that is publications in their broadest sense, within the specific thematic area (Ellegaard et al., 2015). Rivera et al. (2015) state that, when academic output grows in a scientific domain, it becomes critical for researchers to employ quantitative review approaches to understand the structure of knowledge of the domain itself, identify what topics are being studied and potential research directions. According to Durieux et al. (2010), three types of indicators can be found in bibliometric studies: quantitative indicators relating to productivity, quality indicators concerning the publication impact, and structural indicators measuring the established connections.

Currently, bibliometrics has been widely used as a method of quantitative analysis in many fields of scientific research, such as agronomy. Some of these studies considered the most widespread crops, including wheat, as "Trends in research on durum wheat and pasta, a bibliometric mapping approach" (Cecchini et al., 2020), "Global Research Trends for Unmanned Aerial Vehicle Remote Sensing Application in Wheat Crop Monitoring" (Nduku et al., 2023), "Research trends and status of wheat (Triticum aestivum L.) based on the Essential Science Indicators During 2010-2020: a bibliometric analysis" (Yuan et al., 2021), "Worldwide Research Trends on Wheat and Barley: A Bibliometric Comparative Analysis" (Giraldo et al., 2019).

Specifically, this bibliometric analysis aimed at: (1) provide a list of durum wheat irrigation research and identifying geographic-temporal patterns within the literature; (2) analyse the dynamics of the main research topics; and (3) analyse the global relationships between researchers and countries through the analysis of co-existence, co-occurrence, citation and bibliographic coupling.

2. MATERIALS AND METHODS

2.1. Methodology design

In this work a bibliometric analysis has been conducted as a systematic search for peer-review articles (Nduku et al., 2023), to analyse the relevance of research output on durum wheat irrigation, exploring the state and trend of research in existing literature globally.

The PRISMA 2020 (Preferred Reporting Items for Systematic review and Meta-Analyses) protocol was adopted to retrieve the relevant articles. PRISMA is a consolidated methodology to carry out systematic reviews and meta-analyses (Galvão et al., 2015; Page et al., 2021).

SCOPUS was chosen as the only database for the collection of documents, as it is considered, together with Web of Science, the leader platform of abstracts and citations of the world's literature (Zhu & Liu, 2020).

SCOPUS was used to search for and identify relevant publications related to durum wheat irrigation. By using advanced search filters, we were able to narrow down the results based on specific keywords, publication types, and date ranges to capture the most comprehensive dataset.

The search queries TITLE-ABS-KEY ("durum wheat" AND "irrigation") were used for collecting academic documents and patents including "durum wheat" and "irrigation" terms in the title, abstract and/or keywords.

The obtained metadata were imported and analysed using the open-source software VOSviewer (v 1.6.19) to build and display bibliometric maps.

2.2. Data collection

To carry out the bibliometric analysis the documents were collected following the PRISMA protocol (Fig. 1). The data search on Scopus was completed in one day (November 2023) to avoid distortions. The keywords "durum wheat" and "irrigation" were used to explore the database and collect documents that included terms in the title, abstracts and/or keywords, regardless of the year of publication and the subject area. The research generated a total of 356 documents, including articles, conference papers, reviews, book chapters, data papers and conference reviews. Our analysis was limited to research articles and reviews, written in English. Finally, the complete records were exported as .csv file and then used in the VOSviewer software for the descriptive statistics, graphics and the co-occurrence citation analysis.

2.3. Data analyses

The selected publications were subjected to performance analysis and scientific mapping. The first considers the contributions of the research components, while the second focuses on the relations between those components (Donthu et al., 2021).

Regarding the performance analysis, the selected publications were evaluated considering the following factors: total publications, number of documents per year, author, institution of which the authors are members, country, subject area, journal name, keywords, and number of citations.

Keywords have been cleaned by omitting country terms, duplicate words, and plural words.

The analysis of the co-citation was realized with the program VOSviewer, included: analysis of co-authors, to show the collaborations between authors, organizations, and countries; analysis of co-occurrences of all keywords; bibliographic coupling, which allowed to separate the publications into thematic clusters based on shared references.

The maps generated contain nodes that represents an element (e.g. document, author, country, institution, keyword, journal) and whose size reflects its magnitude (the number of times it occurs). Some items are not displayed to avoid overlapping. The colours in the network view (text maps) describe groups of similar elements calculated by the program. The link between nodes indicates the existence of the bond, while the distance or thickness of the link refers to the force of the relations (number of times it occurs) (Donthu et al., 2021). The period considered starts from the year in which the first indexed documents on the issue of study date back to today.

3. RESULTS AND DISCUSSIONS

3.1. Evolution of the scientific production and distribution by countries, institutions, and authors

The search terms "durum wheat" and "irrigation" produced a total of 356 documents, of which only 332 were used in this study, falling into the category of articles and reviews.

The first indexed documents on Scopus related to the research on durum wheat irrigation date back to 1977 and both come from the USA: "Remote-sensing of crop yields" (Idso et al., 1977), review published in Science and, "Wheat canopy temperature: A practical tool for evaluating water requirements" (Jackson et al., 1977), article published in Water Resources Research.

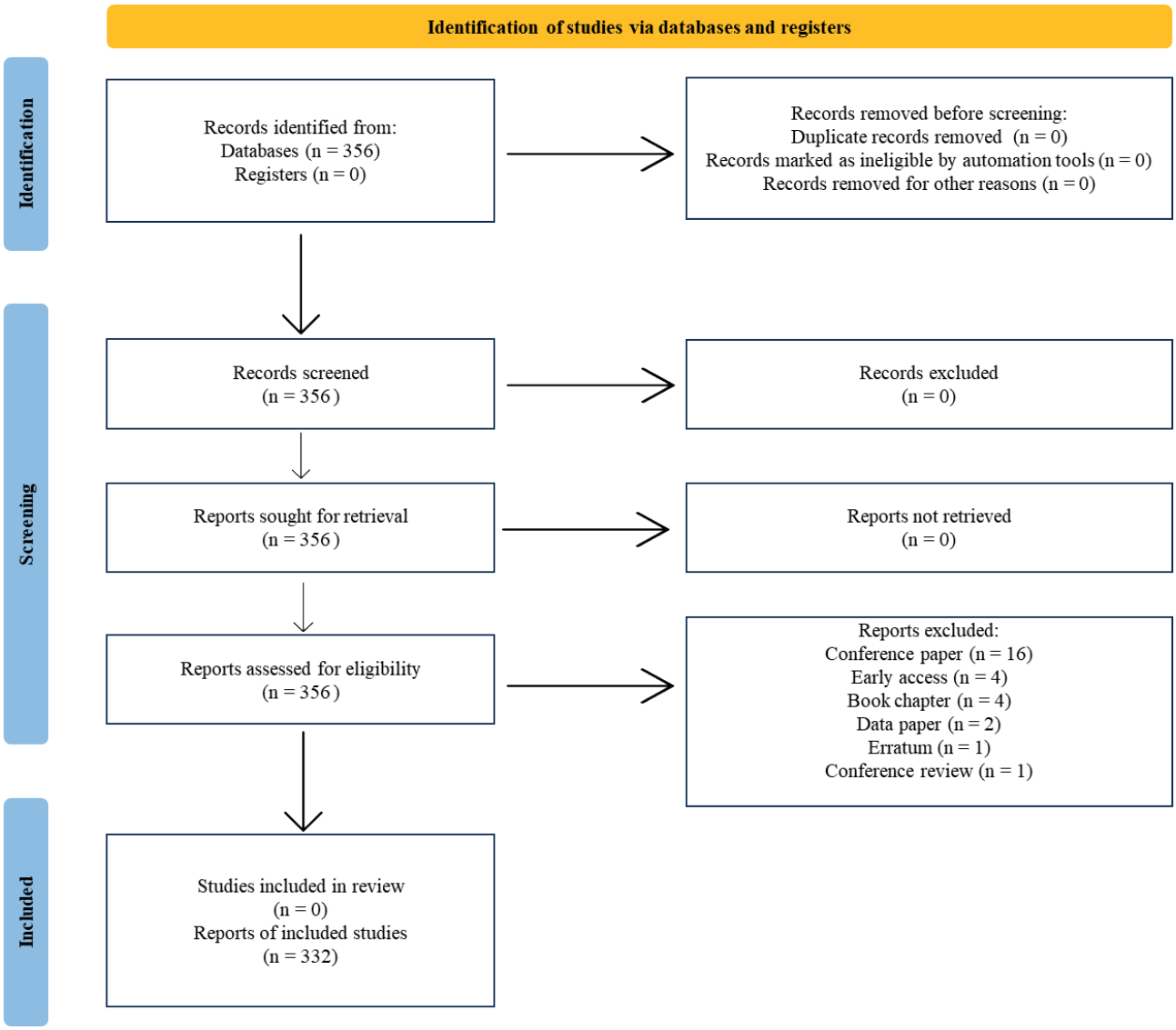

Figure 1. Procedure applied for document selection for the bibliometric review and thematic analysis (PRISMA protocol).

From 1977 to 2000, 49 articles were published (about 15% of total production), with a generally low annual production rate, since no documents were found in 1979, 1980, 1982, 1984, 1991 and 1996. On the other hand, only 27 articles were published between 1997 and 2000 (Fig. 2).

The growth of publishing production has continued from 2007 until today, where there are at least 10 publications annually, indicating the growing interest in this topic. However, during the last period, this trend has been discontinuous, as can be seen from the variability in the number of publications among years (Fig. 2). The peak was reached in 2022 with a total of 21 publications. In 2023 there were 13 documents (until 14 November), but the number could still grow.

In relation to the contributions of countries, Figure 3 shows the spatial distribution of the documents published on irrigated durum wheat from 1977 to 2023.

The results show that the interest in this topic of research is widely diffused, confirming that durum wheat is one of the most important crops cultivated worldwide (Kabbaj et al., 2017). However, the number of scientific publications is not steadily distributed among the 49 countries that contributed to the research. The largest contribution comes from countries in Southern Europe, Asia, North Africa and North America.

In particular, the top 10 countries with the best performance in terms of scientific production (Fig. 4) contributed 92% to the reference literature. Most of these

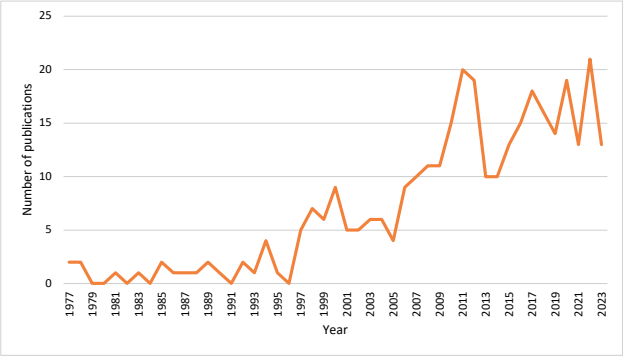

Figure 2. Annual distribution of publications.

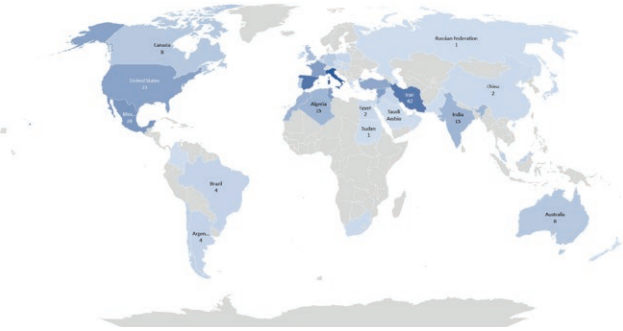

Figure 3. Spatial distribution map of scientific production on irrigation of durum wheat from 1977 to 2023.

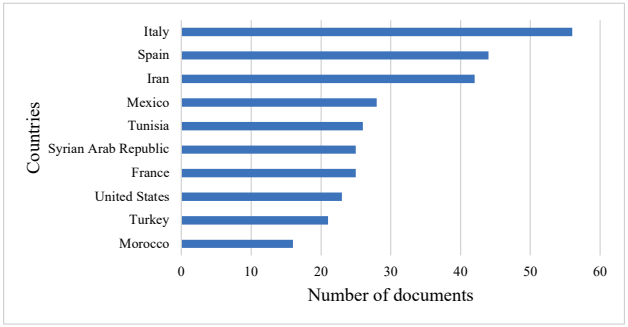

Figure 4. Top ten countries with the highest scientific production.

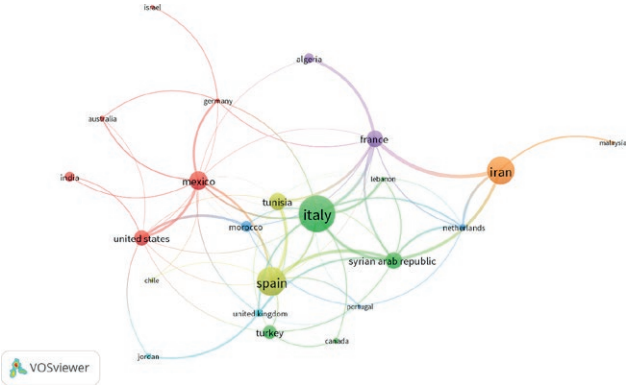

Figure 5. Co-authorship networks of countries. 1st cluster: red; 2nd cluster: green; 3rd cluster: blue; 4th cluster: yellow; 5th cluster: purple; 6th cluster: light blue; 7th cluster: orange.

countries are also among the main producers of durum wheat. Currently, the Mediterranean basin is the largest area of production of durum wheat in the world, as well as the largest consumer of durum wheat products enough to activate a very significant import market (Xynias et al., 2020). The countries of the Mediterranean basin, which are among the top ten countries with the most publications on this topic, are Italy, Spain, Tunisia, France, Syria, and Turkey (Fig. 4).

However, despite Iran doesn't appear among the biggest producers of durum wheat, several articles have been found, representing the third country in the number of scientific productions, constituted by 42 works.

Figure 5 shows the co-authorship network map between countries. It allows us to analyse the possible interaction between researchers from different countries and thus understand the dynamics of research production.

A minimum number of 5 documents for country has been set as a threshold for map creation. The software identified 23 nodes, 7 clusters and 72 links. The largest nodes identified countries with multiple publications. According to the map the first cluster (red) is the most numerous and includes Australia, Germany, India, Israel, Mexico, United States. The second cluster (green) consists of five countries Canada, Italy, Lebanon, Syria, Turkey. The third cluster (blue) includes Morocco, Netherlands, and Portugal. The fourth cluster (yellow) consists of Chile, Spain, and Tunisia. The fifth cluster (purple) consists of Algeria and France. The sixth cluster (light blue) is formed by Jordan and United Kingdom. The seventh cluster (orange) consists of Iran and Malaysia. From the map it is also visible that the countries of the same cluster have collaborations with other countries of different clusters.

Table 1 shows the top 15 most productive institutions in terms of publishing production that have carried out research on durum wheat irrigation. Fourteen of the fifteen main institutions belong to the countries with the highest publishing output: Spain (4), Italy (3), Iran (3), Tunisia (2), Mexico (1), Syria (1). Moreover, only seven are universities while the others are non-academic institutions.

The University of Barcelona with 26 publications, to which belong 2 researchers listed in Table 2 of the 10 most productive authors (Araus J.L. and Serret M.D.),

Table 1. Main universities/research institutes and their editorial production.

Affiliations	Country	Records
University of Barcelona	Spain	26
University of Carthage, Institut National de la Recherche Agronomique	Tunisia	26
International Center for Agricultural Research in the Dry Areas Syria (ICARDA)	Lebanon	25
International Maize and Wheat Improvement Center (CIMMYT)	Mexico	24
Council for Agricultural Research and Economics (CREA)	Italy	15
University of Carthage	Tunisia	15
Institute of Agrifood Research and Technology (IRTA)	Spain	13
Mediterranean Agronomic Institute of Bari (CIHEAM Bari)	Italy	11
Islamic Azad University	Iran	9
Italian Nnational Research Council (CNR)	Italy	8
Agrotecnio. Centre for Food and Agriculture Research	Spain	8
Wageningen University & Research (WUR)	Netherlands	7
Isfahan University of Technology	Iran	7
University of Lleida	Spain	7
Dryland Agricultural Research Institute, Maragheh	Iran	7

Table 2. Number of publications and citation metrics of the most influential authors. The affiliation of author was retrieved from Scopus database through 'author search'. Legend: TC-total citation; NP-number of publications.

Authors	h-index	g-index	m-index	TC	NP	Period	Affiliation	Country
Araus J.L.	56	96	1.81	418	28	1997-2023	University of Barcelona	Spain
Oweis T.	34	70	1.42	129	11	1999-2012	International Center for Agricultural Research in the Dry Areas Syria	Lebanon
Serret MD.	31	53	2.38	108	10	2010-2023	University of Barcelona	Spain
Royo C.	46	84	2	230	9	2000-2021	Institute of Agrifood Research and Technology	Spain
Trifa Y.	13	26	1.62	18	9	2015-2022	University of Carthage, Institut National de la Recherche Agronomique	Tunisia
Villegas D.	34	60	1.48	132	8	2000-2020	Institute of Agrifood Research and Technology	Spain
Aparicio N.	21	41	0.91	71	7	2000-2023	Castile-Leon Agriculture Technology Institute (ITACyL)	Spain
Govaerts B.	42	83	3.5	70	7	2011-2021	International Maize and Wheat Improvement Center	Mexico
Nachit M.M.	31	57	1.19	118	7	1997-2008	International Center for Agricultural Research in the Dry Areas Syria	Lebanon
Verhulst N.	25	55	2.08	49	7	2011-2021	International Maize and Wheat Improvement Center	Mexico

is among the busiest istitutions to work in this field of research.

As regards the number of authors, a total of 1122 authors contributed to the 332 documents analysed. However, only 3 authors had 10 or more publications in this field of research: Araus J.L. (28), Oweis T. (11) and Serret M.D. (10). About 98% had 5 or fewer publications (Table 2).

Table 2 shows also the first 10 authors who contributed to the research on durum wheat irrigation.

Figure 6 shows the network of collaborations between authors. Collaborative networks are formed between authors working together to produce an article. Having set a threshold of 5 for the minimum number of documents per author, only 31 of them met the requirement. However, some of these were not connected to each other and, therefore, they weren't listed on the map. The network consists of 25 nodes, 5 clusters and 78 links. From this analysis it emerges that the authors of the same country tend to have a close collaboration with each other.

The first cluster (red) includes 7 authors, all from Spain, such as Araus, Bort and Serret. The second cluster (green) consists of 5 authors affiliated with Tunisian universities or research institutes such as Ayadi, Chamekh, Karmous, Trifa and Sahli. Cluster 3 (blue) is represented by 4 Spanish researchers such as Aparicio, Villegas, Royo, Garcia del Moral, and by Rharrabti who belongs

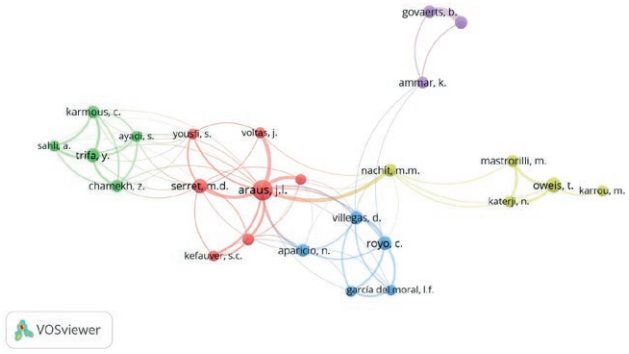

Figure 6. Author co-authorship network visualization map.. 1st cluster: red; 2nd cluster: green; 3rd cluster: blue; 4th cluster: yellow; 5th cluster: purple.

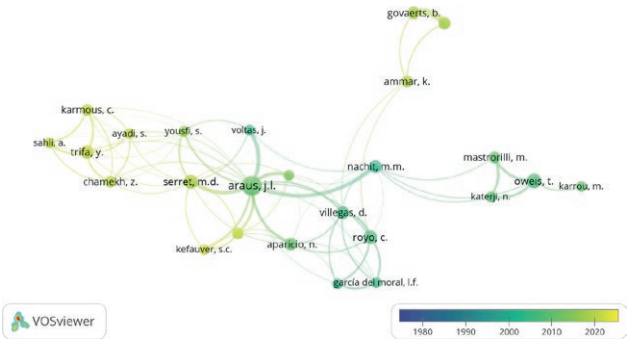

Figure 7. Temporal distribution of collaborations.

to Moroccan institutions. The fourth cluster (yellow) is always made up of 5 authors coming from different countries: Oweis and Nachit of Lebanon, Karrou from Morocco, Katerji from France, and Mastrorilli from Italy. Finally, the fifth cluster (purple) is represented by 3 researchers from Mexico such as Ammar, Govaerts and Verhulst.

In addition, the overlay visualization map (Fig. 7) shows the development through time of collaborations between authors. The authors of cluster 2 present the latest collaborations dating back to 2018, while the older ones concern clusters 1 and 4.

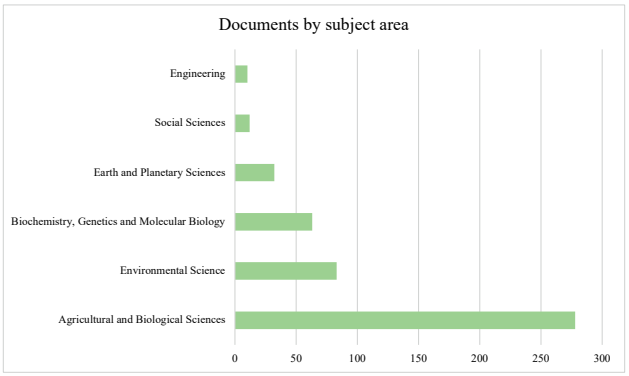

Figure 8. Number of scientific papers on durum wheat irrigation by thematic area.

3.2. Thematic areas of research and scientific sources

Scientific papers on durum wheat irrigation have been distributed in 22 thematic areas according to the Scopus classification. Figure 8 shows the thematic areas with a minimum of 10 records.

With 51%, the largest number of documents (278) is included in the Agricultural and Biological Sciences area, followed by Environmental Science (83), Biochemistry, Genetics and Molecular Biology (63), Earth and Planetary Sciences (32),Social Sciences (12) and Engineering (10)

It is evident that the same document can be assigned to several thematic areas; for example, many of the documents included in the Environmental Science area are also present in the first Agricultural and Biological Sciences area.

All 332 documents were published in 149 journals and only 6 of them had a minimum number of records of 5.

Table 3 lists the top 5 major journals that are all international and belong to the Agricultural and Biological Sciences scientific category. The table 3 also shows the Impact Factor (IF 2022) which measures the average number of times the journal articles published in the last two years have been cited in the current year (Dong P. et al., 2005).

Table 3. Number of publications and citation metrics of sources. The impact factor of the journal was retrieved from the 2022 Journal Citation Reports. Legend: TC-total citation; NP-number of publication; SYP-start of the year of publication; AC-average citation; IF-impact factor.

Sources	h-index	g-index	m-index	TC	NP	SYP	AC	IF	Country	Publisher
Agricultural Water Management	152	236	3.30	1073	19	1999	56.47	6.7	Netherlands	Elsevier
Field Crops Research	174	51	3.87	1021	19	1986	53.74	5.8	Netherlands	Elsevier
European Journal of Agronomy	131	221	4.37	525	14	1998	37.5	5.2	France	Elsevier
Italian Journal of Agronomy	29	45	1.93	100	10	2009	10	2.2	Italy	PagePress
Cereal Research Communications	37	53	1.23	108	7	1998	15.43	1.6	Germany	Cereal Research NonProfit Company

The top 3 journals rank in the first quartile (Q1), while the others in the second quartile (Q2) according to the Journal Citation Reports 2022. This distinction indicates that they are high impact factor journals, in fact, the Journal Impact Factor (JIF) published by Thomson Reuters' Journal Citation Reports is a widely used indicator for assessing the importance or visibility of a journal in its field (Liu et al., 2016).

Agricultural Water Management with 19 publications ranks first among the journals that have contributed most to research on durum wheat irrigation, immediately followed by the journal Field Crops Research with 19 papers and the European Journal of Agronomy with 14 papers. These three journals were among the main ones also in other bibliometric analyses that dealt with issues similar to the ones of this work (Sun et al., 2020; Velasco-Muñoz et al., 2018).

Both Agricultural Water Management and Field Crops Research publish only articles related to science, economics, and water management policy in agriculture. Conversely, the European Journal of Agronomy deals with several topics concerning the selection and genetics of crops, the physiology of harvesting and production as well as crop management, including irrigation, fertilization, and soil management. It also addresses aspects of agroclimatology and modelling, plant-soil relations, crop quality and post-harvest physiology, farming and cultivation systems, agroecosystems and the environment, interactions and weed management. The Italian Journal of Agronomy (IJA) is the official journal of the Italian Society of Agronomy, which deals with all aspects of Agricultural and Environmental Sciences, the interactions between cultivation systems and sustainable development. Cereal Research Communications publishes articles presenting new scientific findings on selection, genetics, physiology, pathology and mainly production of wheat, rye, barley, oats, and corn.

Further analysis shows that the most influential journal in this field by number of citations is Australian Journal of Agricultural Research (1578) (not shown in the table), although the journal accounts for only 3 documents; follow Agricultural Water Management (1073) and Field Crops Research (1021), which are the journals with more publications (Tab. 3).

Figure 9 describes the progress of scientific production of the first five journals over the years. Overall, each journal has published 12 articles per year. Agricultural Water Management released the first article in 2004, peaking in 2009 with 3 papers. Field Crops Research is the journal with the first oldest publication in this field, dating back to 1986. The first article on Italian Journal of Agronomy dates back to 2009, peaking the following year with 4 papers. The first article published on the irrigation of durum wheat in the European Journal of Agronomy dates back to 1998 and reached 3 publications in 2023. Cereal Research Communications published only 7 papers on the topic and no more than one article a year.

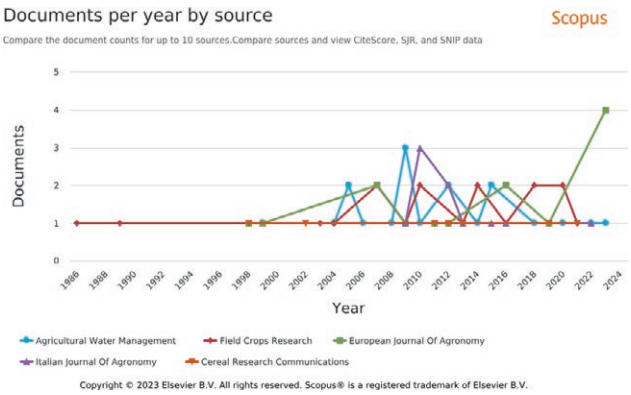

Figure 9. Trend of the scientific production of the top five journals over the years.

3.3. Keywords of the authors and co-occurrence network

The analysis of co-occurrences is a technique that allows to examine the content of the publication, since it assumes that words that frequently appear together have a thematic relationship with each other (Donthu et al., 2021).

The study gathered all the keywords of the documents under investigation to conduct the analysis of keywords and co-occurrences. For this reason, networks of co-occurrences have been created to show the relationships between keywords in the search field.

Table 4 shows the first most recurring words in documents.

Table 4. Keywords and number of occurrences.

Keyword	Occurrences (n)
durum wheat	545
Triticum aestivum	138
irrigation	143
crop yield	90
grain yield	63
drought stress	61
crops	38
genotype	36
nitrogen	36
water use efficiency	29

The keyword with the greatest number of occurrences was "durum wheat" (545), followed by "*Triticum aestivum*" (138), while "irrigation" is in third place (143). In the list were frequent keywords that are used to classify wheat. The top keywords include "grain yield" (63), "drought stress" (61), "nitrogen" (36), "water use efficiency" (29). They are therefore the most indexed words and represent the most discussed topics in this search domain.

Some of these keywords ("yield", "nitrogen", "irrigation", "drought", "climate change") were also recurrent in other bibliometric analyses of wheat (Giraldo et al., 2019; Cecchini et al., 2020; Yuan & Sun, 2021). These words refer to environmental issues that affect agricultural production, some of which are explored in the context of crop sustainability (Giraldo et al., 2019).

In a bibliometric analysis on the efficiency of water use in agriculture (Velasco-Muñoz et al., 2018), the terms "wheat", "irrigation", "irrigation system" and "crop" appeared among the top 10 keywords. Part of the documents analysed, in fact, focused their research on the use and efficiency of water irrigation to maximize production in some crops, including wheat.

Words with at least 10 occurrences have been considered to create the keyword co-occurrence network. Among the 2122 keywords identified only 51 have reached this threshold. The software then identified 51 nodes, 4 clusters and 1000 links (Fig. 10).

Cluster 1 (red) includes keywords such as irrigation, climate change, crop yield, evapotranspiration, fertilizer application, nitrogen, protein, soil water, supplemental irrigation, water use efficiency. In this network it is possible to notice how many keywords relating to the management of water resources recur. The production of durum wheat (*Triticum durum* L.) in semi-arid regions is limited by an inadequate water supply that occurs especially during the end of the harvest season (Karam et al., 2009). As a result, the planning of an adequate irrigation and nitrogen fertilization strategy, which considers the phenology of crops, allows to produce optimal wheat yields (Karam et al., 2009). This problem, which is widespread in the areas of cultivation of durum wheat, is intensified by the ongoing climate change (IPCC, 2014; Fahad et al., 2017). In fact, many studies have simulated the effects of climate change on the agronomic and productive performance of both durum wheat and other crops (Rharrabti et al., 2003; Ventrella et al., 2012; Ventrella et al. 2015; Muleke et al., 2022). Supplemental irrigation has been widely recognized as one of the most feasible means of increasing cereal yield and water efficiency in arid areas (De Vita et al., 2007; Campbell et al., 1993; Oweis et al., 1999). Oweis (1997) defines supplementary irrigation as "the addition to essentially rainfed crops of small amounts of water during times when rainfall fails to provide sufficient moisture for normal plant growth, in order to improve and stabilize yields". However, more recent studies suggest replacing additional watering with a deficit level of irrigation (regulated deficit irrigation) which should be determined considering the availability of water in the soil and the specific response of the crop (Chai et al., 2016). Consequently, understand the mechanism of the physiological process regulation of wheat relating to different irrigation regimes and, therefore, the effect of water stress on yield, would optimize water saving irrigation technology for sustainable wheat production. The amount of water can be planned already at the beginning of the anthesis and of the grain-filling, while in dry years irrigation may be necessary already in the stem elongation phase to ensure a flourishing development of the crop (Oweis et al., 1999; Chen et al., 2003).

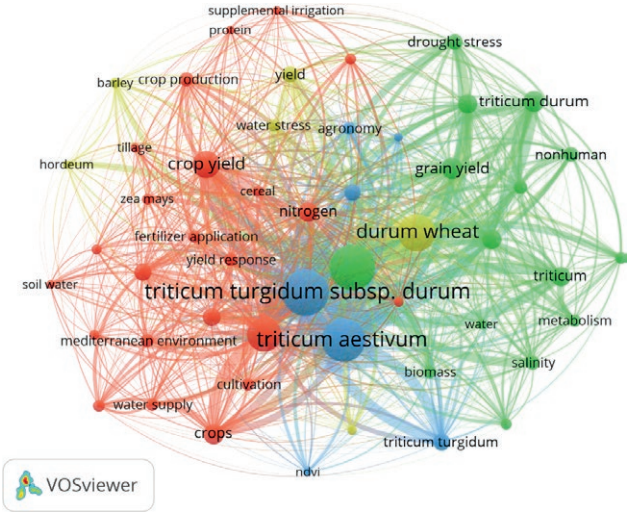

Figure 10. Trend analysis and co-occurrence network of authors' keywords. 1st cluster: red; 2nd cluster: green; 3rd cluster: blue; 4th cluster: yellow.

Cluster 2 (green) includes words such as "drought", "drought stress", "genotype", "grain yield", "photosynthesis", "salinity", "*triticum durum*", "water", "physiology", "metabolism". These words express two of the main environmental stresses, drought, and salinity, to which durum wheat is continuously subjected in semi-arid cultivation environments, such as the Mediterranean one (Guidi and Calatayud 2014; Chairi et al. 2020). Both salinity and drought reduce soil water availability for plants (Rhoades, 1972; Ayers and Westcot, 1985) causing negative effects on physiological processes resulting in loss of yield (Nowicka et al., 2018). Moreover, both salinity and drought are often present in the same envi-

ronment so many studies investigate the effects of the interaction between the two stresses (Katerji et al., 2009; Yousfi et al., 2012; Yousfi et al., 2016; Yaghoubi Khanghahi et al., 2021).

Cluster 3 (blue) consists of words such as "cultivar", "NDVI", "*Triticum turgidum*", "*Triticum aestivum*". The growing interest in the use of vegetation indices, derived from Unmanned Aerial Vehicle (UAV) or satellite images, is linked to their great potential use. Both proximal and remote sensing for the detection of vegetation indices are non-destructive methods and are well correlated with the agronomic and physiological characteristics of cultures (Reynolds et al., 2015). The Normalized Difference Vegetation Index (NDVI) is one of the most studied and used vegetation indices (Huang et al., 2021). Some researchers have evaluated the NDVI to quantify grain development and yield (Fernandez-Gallego et al., 2019; Elazab et al., 2015) and for plant phenotyping in breeding programmes (Rezzouk et al., 2022; Sanchez-Bragado et al., 2020; Mzid et al., 2020).

French et al. (2020) conducted a three-year study to assess the ability of the vegetation index (VI), derived from satellite-detected images, to track grain evapotranspiration. The results indicated that, in most cases, it was possible to accurately estimate the cultural coefficient (Kc) and the cultural evapotranspiration (Etc) from the NDVI during the middle of the season until the senescence phase.

Cluster 4 (yellow) is represented by words such as "barley", "durum wheat", "hordeum", "yield", "water stress". The link between wheat and barley is evident in this cluster. Wheat and barley are the two main cereals cultivated in the Mediterranean region and represent strategic crops for the food security of the entire area (Albrizio et al., 2010). The two cereals are often studied together, or, in other cases, wheat is used as a reference for the discussion of the results of barley research and conversely (Giraldo P. et al., 2019). Albrizio R. et al. (2010), in a study conducted in southern Italy, compared the effects of the interaction of different doses of nitrogen and water supply regimes on durum wheat and barley. Katerji et al. (2009) evaluated the effect of water and salt stress on the two cereals yields.

As may be clear from the map, each of these words form links even with many other words of different clusters.

3.4. Bibliographic coupling

Bibliographic coupling occurs when two papers refer to a common third paper in their bibliographies, indicating that there is a probability that the two papers will address a related topic. The "coupling force" of two papers is greater the more citations to other papers they share (Kessler, 1963; Martyn, 1964).

The evaluation of the bibliographic coupling of countries, journals and scientific papers was carried out as a method of measuring similarities.

For the bibliographical matching of countries (Fig. 11), those with a minimum number of 10 documents were considered. The software identified for the 14 countries that met the threshold, 5 clusters and 76 links. As can be seen from Figure 10, the largest group (red) was formed by India, Mexico, Morocco, and the USA. In this cluster the highest link was observed between USA and Mexico. The second cluster (green) includes Iran, Netherlands, and Syria. The third cluster (blue) consists of Spain, Tunisia, and Turkey. The fourth cluster (yellow) consists of Algeria and France. The fifth cluster (purple) includes United Kingdom and Italy. Moreover, from the map it is evident that Spain forms strong connections with Mexico, Tunisia, and Italy.

Regarding the bibliographical coupling of journals (Fig. 12), of which a minimum threshold of 5 papers per journal was set, only 6 of them complied with the threshold. The software has calculated two clusters and 10 links. The first cluster (red) is represented by the magazines Agricultural Water Management, European Journal of Agronomy, Italian Journal of Agronomy and Field Crops Research, while the second cluster (green) by Agronomy and Cereal Research Communications. This

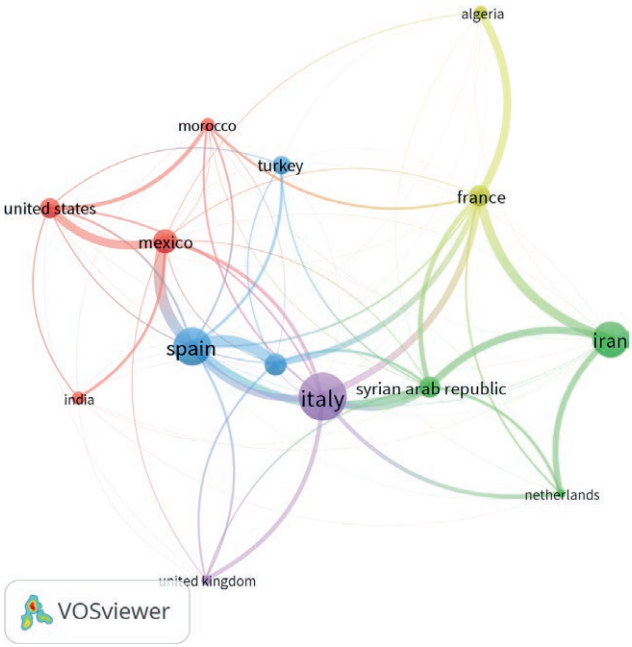

Figure 11. Bibliographic coupling of countries. 1st cluster: red; 2nd cluster: green; 3rd cluster: blue; 4th cluster: yellow; 5th cluster: purple.

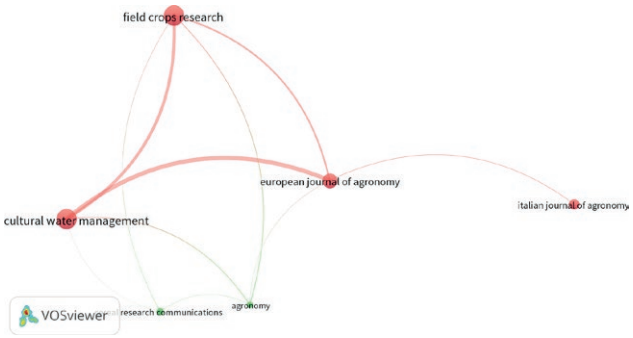

Figure 12. Bibliographic coupling of journals. 1st cluster: red; 2nd cluster: green.

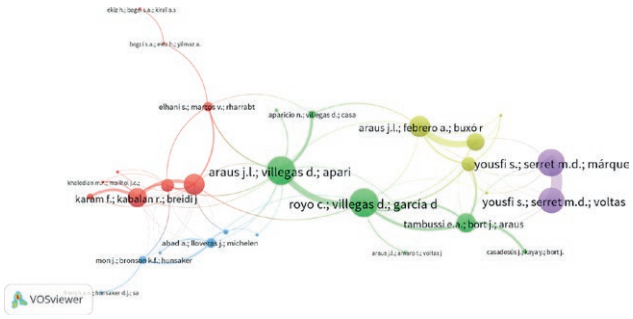

Figure 13. Bibliographic coupling of documents. 1st cluster: red; 2nd cluster: green; 3rd cluster: blue; 4th cluster: yellow; 5th cluster: purple.

analysis also shows that the journals Agricultural Water Management, Field Crops Research and European Journal of Agronomy have the greatest coupling force.

In the analysis of the bibliographic coupling of papers (Fig. 13), the minimum number of citations of a paper has been fixed at 50. Out of 332 papers, 55 reached the threshold. However, only 30 showed connections within the network. A total of 5 clusters were identified in which many of the papers had links of co-paternity.

Cluster 1 (red), more numerous, includes 9 papers which are by Albrizio et al., 2010; Bagci et al., 2007; Ekiz et al., 1998; Elhani et al., 2007; García Del Moral et al., 2003; Karam et al., 2009; Khaledian et al., 2009; Latiri-Souki et al., 1998; Zhang et al., 1999. These papers investigate the effect of water use efficiency and nitrogen fertilization on durum wheat yield.

Latiri-Souki et al. (1998) in their studies evaluated the response of durum wheat to nitrogen fertilization under conditions of different irrigation levels and in different pedoclimatic environments. Elhani et al. (2007) reported that low-yield durum wheat genotypes could be more advantageous in terms of yield compared to genotypes with high-yield capacity in non-irrigated areas.

The papers by Bagci et al. (2007) and Ekiz et al. (1998), instead, evaluated the combined effects of drought stress and Zn deficiency on yield. From this work emerged a positive correlation between the nutritional status of Zn of plants and their sensitivity to water stress (Bagci et al., 2007) in fact, plants subjected to water scarcity had a greater sensitivity to Zn deficiency (Ekiz et al., 1998).

Cluster 2 (green) comprises 8 papers by Aparicio et al., 2000; Araus et al., 1998; Araus et al., 2003; Casadesús et al., 2007; Peleg et al., 2005; Royo et al., 2002; Tambussi et al., 2007; Fischer et al., 1978. In these studies emerges one of the main issues that concerns the countries that produce durum wheat and, consequently, the scientific community. In fact, drought stress, as a combination of water deficit and high temperatures, is the main bond that limits the cultivation of durum wheat in semi-arid environments of cultivation (Araus et al., 2002). Researchers from cluster 2 selected durum wheat genotypes that could adapt to semi-arid conditions and withstand rising high temperatures while maintaining a satisfactory yield. Some have used vegetation indices (VI) (Casadesús et al., 2007; Aparicio et al., 2000) as a tool for plant phenotyping, others the discrimination of carbon isotopes (Royo et al., 2002; Peleg et al., 2005) and crown temperature (Royo et al., 2002).

Moreover, the analysis shows that the paper "Comparative performance of carbon isotope discrimination and canopy temperature depression as predictors of genotype differences in durum wheat yield in Spain" (Royo et al., 2002) formed strong links with "Environmental factors determining carbon isotope discrimination and yield in durum wheat under Mediterranean conditions" (Araus et al., 2003).

Cluster 3 (blue) consists of 6 papers produced by Abad et al., 2004, French 2020, Katerji et al., 2009, Masoni et al., 2007, Mon et al., 2016, Rharrabti et al., 2003. In some of these papers, the effect of the interaction of nitrogen fertilization and irrigation on yield components and the quality of durum wheat was evaluated. As is well known, the management of water and nitrogen influences the characteristics of durum wheat, such as protein content, which plays a key role in the final use of the product (De Santis et al., 2021). In fact, an adequate water supply, in terms of quantity and timing of distribution, can generally increase the yield of cereals and the use efficiency of nitrogen (NUE) in durum wheat by improving its assimilation and translocation in the plant, as well as minimising nitrogen losses (Lu et al., 2015).

Cluster 4 (yellow) consists of 5 articles, of which 4 show as the first author Araus (Araus, Febrero et al.,

1997a; Araus, Febrero, et al., 1997b; Araus, Amaro et al., 1997; Araus, Febrero et al., 1999), while an article is by Knight et al. (1994). These studies analysed the stable isotopic carbon composition in the dry matter of leaves and/or caryopsis, related to both photosynthetic efficiency and water use and plant yield. In addition, the analysis of the carbon isotopes discrimination in the remains of cultivated plants from archaeological sites, was used to assess the availability of water during the dawn of agricultural activity. The isotopic composition of carbon has also been extensively studied as a selection tool in cereal genetic improvement programs, both to select genetic loci associated with drought tolerance and as a measure of increased yield in good agricultural condition (Rebetzke et al., 2008). According to more recent studies, Araus et al. (2013) have shown that the stable isotopic composition of carbon is positively related to the efficiency of water use.

Cluster 5 (purple) consists of only two articles, both by Yousfi et al. (2010; 2012), "Combined use of δ13C, δ18O and δ15N tracks nitrogen metabolism and genotypic adaptation of durum wheat to salinity and water deficit" (Yousfi et al., 2010) and "Effect of salinity and water stress During the Reproductive stage on growth, ion concentrations, Δ13C, and δ15N of durum wheat and related amphiploids" (Yousfi et al., 2012).

3.5. Citation analysis

The number of citations represents, together with the number of scientific papers produced, one of the indicators reflecting the success of the research and the academic authority of a country, institution, journal, and author, relative to a given research domain (Nduku et al., 2023).

Table 5 shows the first 10 most cited scientific publications since 1977, which are therefore the most influential in the field of research covered by this analysis.

The most cited paper with 1478 citations is "Drought resistance in spring wheat cultivars. I. Grain yield responses" (Fischer et al., 1978), published by the Australian Journal of Agricultural Research. The normalized citation (TCY) demonstrates that this research still represents an important basis for studies on durum wheat irrigation. This study, conducted in Mexico for three growing seasons, investigated the effect of drought on the yield of a wide range of cereal cultivars, including durum wheat genotypes. Detailed measurements were made of the water status of the plants, leaf area, dry matter production, date of the anthesis, grain yield and its components. The drought levels were such that the average yield of all cultivars, varied from 37 to 86% compared to the control yield (irrigated thesis). Furthermore, the results of their research showed that durum and triticale wheat were more sensitive to drought than common wheat and barley. The second paper by number

Table 5. Most cited documents. Legend: TC-total citation; TCY-total citation per year.

Authors	Title	DOI	TC	TCY
Fischer R.A. et al. (1978)	Drought resistance in spring wheat cultivars. 1. Grain yield responses	10.1071/AR9780897	1478	32.84
Jackson R.D. et al. (1977)	Wheat canopy temperature: A practical tool for evaluating water requirements	10.1029/WR013i003p00651	657	14.28
Zhang H. et al. (1999)	Water-yield relations and optimal irrigation scheduling of wheat in the Meditenanean region	10.1016/S03783774(98)00069-9	370	15.41
Aparicio N. et al. (2000)	Spectral vegetation indices as nondestructive tools for determining durum wheat yield	10.2134/agronj2000.92183x	327	14.21
Garcia del Moral L.F. et al. (2003)	Evaluation of grain yield and its components in durum wheat under Mediterranean conditions: An ontogenic approach	https://doi.org/10.2134/agronj 2003.2660	276	13.80
Idso S.B. et al. (1977)	Remote-sensing of crop yields	10.1126/scienza.196.4285.19	273	5.93
Araus J.L. et al. (2003)	Environmental factors determining carbon isotope discrimination and yield in durum wheat under Mediterranean conditions	10.2135/cropsci2003.1700	203	10.15
Tambussi E.A. et al. (2007)	Water use efficiency in C3 cereals under Mediterranean conditions: A review of physiological aspects	10.1111/117447348.2007.00143.x	172	10.75
Masoni A. et al. (2007)	Post-anthesis accumulation and remobilization of dry matter, nitrogen and phosphoms in durum wheat as affected by soil type	10.1016/j.eja.2006.09.006	163	10.19
Blum A. et al. (1989)	Yield stability and canopy temperature of wheat genotypes under drought-stress	10.1016/03784290(89)90028-2	154	4.53

of citations (657) is "Wheat canopy temperature: A practical tool for evaluating water requirements" (Jackson et al., 1977) published in the journal Water Resources Research. The results of this work led to the elaboration of an indicator called "Stress Degree Day" (SDD), obtained from the sum of the differences between the crown temperature and the air temperature (Tc - Ta) measured during the test on irrigated durum wheat plots with different water levels. An equation relating evapotranspiration (ET) to net radiation and SDD was also tested. The purpose was to use SDD as an indicator to determine the timing and the number of irrigations to be applied. The third paper "Water-yield relations and optimal irrigation scheduling of wheat in the Mediterranean region" (Zhang h. et al., 1999) has 370 citations and was published in Agricultural Water Management. In the work, ten years of experiments on supplementary irrigation (SI) in Syria were conducted to assess the relationship between durum wheat (*Triticum durum* L.) and soft wheat (*Triticum aestivum* L.) with water consumption to plan and optimize irrigation at different rainfall conditions. During the test, the sensitivity of the cultures to water stress was analyzed in the different growth phases, the most sensitive of which were the raising phases, followed by the anthesis and the caryopsis-filling phase. It was found that crop yields increased linearly with increased evapotranspiration (ET), however, in conditions of limited water resources, the study identified the volumes of irrigation that allowed to optimize the use of water without compromising the yield and profits of the company.

4. CONCLUSIONS

This bibliometric analysis provided a broad analysis of research topics related to durum wheat irrigation from 1977 to 2023. The adoption of different bibliometric techniques has allowed us to gain a better understanding of the intellectual structure of the research field, allowing us to explore the main contributions and the respective relationships.

It is important to note that this revision focused only on papers in which the term "durum wheat" and "irrigation" appeared in the title, abstract or keywords. In the examination, rigorous efforts were made to follow the PRISMA protocol accurately. The survey allowed 332 papers indexed on the Scopus database to be examined.

The results of this bibliometric analysis found a steady increase in scientific publication of peer-review articles since 2007, but it is still limited to provide tools for the policy stakeholder and decision maker to act in this very crucial field crop in southern european agricultural systems.

Italy and Spain are the leading countries for the number of papers published. This trend is reflected in the institutions to which they belong, in fact among the first fifteen, four are represented by Spain and three by Italy. The analysis of the co-existence network demonstrates a wide collaboration between countries around the world. However, authors in the same country tend to have closer cooperation with each other. The journals Agricultural Water Management and Field Crops Research, each with 19 papers, represent those in which the authors published the most. The analysis of keywords, co-occurrence network and bibliographic coupling allowed to identify the focal areas of research in the literature related to durum wheat irrigation. In particular, they concerned i) the management of water resources, ii) the effect of salt and water stress on production, iii) vegetation indices and other indices for plant phenotyping. Finally, the analysis of the references highlighted the most influential publications in the field of research under study, including those of Fischer et al., 1978, Jackson et al., 1977 and Zhang et al., 1999. Considering that the year of publication, not recently, has also contributed to the greater number of citations, this does not exclude that more recent papers, but with fewer citations, are equally important.

The results suggest the need to strengthen institutional partnerships and to increase research on the irrigation of durum wheat, especially in the most vulnerable areas where climate change has the most evident impacts.

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