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BIBLIOMETRIC ANALYSIS OF STUDIES ON DURUM WHEAT RESPONSE TO DROUGHT: FROM FIELD OBSERVATIONS TO SYSTEMS BIOLOGY

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A Scopus-based bibliometric analysis of research into impact of drought on durum wheat plants was performed. A corpus of 865 documents published from 1946 to 2025 was retrieved. Temporal and regional patterns, most relevant institutions, authors, keywords, and publications are discussed. From the exponential growth model, the annual growth rate for the number of publications over the entire period was 8.23 %, with R^2 of 0.86051. Italy was identified as the greatest contributor among countries. H-, G-, and M-indices were employed to analyse authors ratings. Frontiers in Plant Science was detected as the most important journal in this field of research. Using the Sankey diagram, the relationships between author country, author affiliation, and individual authors were considered. Major steps of keyword evolution are analysed. The keywords "yield" and "water stress" in the Trend topic chart indicate areas of persistent research interests. The terms "climate change", "abiotic stress", "physiological stress", and "plant proteins" indicate future research directions. Review of the most-cited articles outlined major themes in the 'response of durum wheat to drought'-related literature, with a shift from assessing drought-inflicted yield losses to elucidation of molecular mechanisms of drought resistance. Analysis of time-sliced co-occurrence maps of keywords demonstrated the genesis of the "biochemical/genetic" cluster, which was later transformed into the "systems biology" cluster. Bibliometric mapping of keywords is scrutinized through the lens of the development of the 'drought in durum wheat' research. The most influential publications were detected, with summarising major findings.

Key words: *Triticum durum,* abiotic stress, aridity, Biblioshiny, research hotspots, temporal and regional patterns, co-occurrence maps.

Aridity is a major threat to crops. Lack of water disrupts cellular functions [1, 2], reduces photosynthetic activity [3, 4], and stunts growth [5] and reproduction [6, 7]. This can cause premature leaf drop, wilting [8, 9], reduce plant biomass [10], and, in severe cases, irreparable cell damage and death [11, 12]. Droughts can weaken plants, making them more susceptible to pests and diseases [13]. Ultimately, droughts have enormous conse-

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quences for agriculture, lowering or even destroying crop yields. Droughts pose an especially serious challenge to crops grown in semi-arid regions, such as the Mediterranean, under rainfed conditions. Durum wheat (*Triticum durum*), the second most cultivated species of wheat after common wheat, is a prime example of such crops. It is grown in the Mediterranean Basin, North American Great Plains, West and Central Asia, and smaller areas in countries like Australia, India, and Ethiopia. Major producers include the European Union (led by Italy), Canada, Türkiye, the United States (especially North Dakota and Montana), and Mexico [14].

There is abundant literature reporting about different aspects of drought in durum wheat: effects of drought stress on durum wheat plants [15—17], mechanisms of drought tolerance/resistance/resilience [18—22] and post-drought-recovery [23], breeding of drought-resilient varieties [24—27], search for sources of this trait [27, 28], experiments with controlled and simulated/modelled drought [29, 30], and economic consequences of droughts [32]. Several comprehensive traditional literature reviews addressing durum wheat cultivation under arid conditions have been published: on effects of drought on durum wheat grain quality [16], drought tolerance mechanisms [33], influence of climate change on durum wheat productivity [34], response of wheat to drought stress at morphological, physiological, and biochemical levels [35], effects of drought on photosynthesis [36], and mechanisms of drought tolerance and management of drought stress [37]. In addition, aridity issues in general have been considered in bibliometric analyses [38, 39]. There is also a specific bibliometric analysis devoted durum wheat irrigation [40] and durum wheat studies in Türkiye [41].

However, to our knowledge, the topic of impact of drought on durum wheat plants has not been analysed through the lens of bibliometrics yet. Hence, we set a goal to conduct bibliometric analysis of studies investigating drought-affected durum wheat.

Materials and methods

On September 28, 2025, we employed specific keywords to retrieve literature from the Scopus database at the Library of the Yuriev Plant Production Institute of the National Academy of Agrarian Sciences of Ukraine. The search terms were *"durum"* (as this word represents both Latin names of the species under investigation (full and shortened forms: *Triticum durum* Desf., *Triticum turgidum* L. ssp. *durum* Desf., *T. durum* Desf., *T. turgidum* L. ssp. *durum* Desf.) and its common name (durum wheat or just durum) AND "drought" (as this word is always a part of more specific terms, such as drought tolerance, drought resistance, drought resilience, drought stress, post-drought recovery, drought effect, etc.). Then we set the following filters: document types were limited to articles, data papers, conference papers, books, book chapters, reviews, conference reviews, and short surveys; publication stage was limited to final; and languages were limited to English.

We found a corpus of 865 documents covering the period from 1946 to 2025. Of them, articles accounted for 91.2 %, conference papers —

3.1 %, book chapters — 2.5 %, reviews — 2.4 %, conference reviews — 0.3 %, books — 0.1 %, data papers — 0.1 %, and short surveys — 0.1 % (based on the in-built Scopus toolkit for bibliometric analysis). For data export, we used the CVS format, selecting all available information fields. The extracted file was uploaded to the web-interface Biblioshiny of the Bibliometrix package in the free software RStudio (version 2025.09.0; Posit Software, PBC) for analyses of bibliometric parameters [42]. To enhance the accuracy of analysis of keywords, thesaurus files were created and uploaded to Biblioshiny to omit irrelevant keywords and to consolidate synonyms. To construct Figs. 2—4 and Tables, we used data sheets processed in Biblioshiny and downloaded from Biblioshiny as .XLSX files. Figs. 2—4 were plotted in Excel. The keyword co-occurrence network was constructed using the 'Association' normalization method to quantify the strength of thematic links. Community detection was implemented via the Walktrap algorithm, which identifies clusters based on random walks through the network. The map layout was optimized with a repulsion force parameter of 0.1 to improve visual clarity and node separation. Figs. 5—8 were downloaded from Biblioshiny as .PNG files. The design and flow of this study are depicted in Fig. 1. The flowchart in Fig. 1 was built in the free online diagram software draw.io [43].

Results and discussion

In the retrieved from Scopus dataset, the first two articles were published in 1946; they did not specifically report about response of durum wheat to drought, merely touching this topic, and were not cited in other publications in this field at all. Then there was a gap in the publishing activities until 1978, when 2 documents appeared; 1979 had 3 publications and 1980 — 1 publication; then there was another, relatively short, 3-year gap without publications (hence, the period from 1946 to 1983 is not presented in the graph), and, starting from 1984, the number of publications began to increase. The most striking feature here is the considerable year-to-year fluctuations, with peaks and troughs. There are noticeable peaks in 1995, 1998, 2007, and 2011, and troughs in 1996, 1999—2000, 2006, and 2020 (Fig. 2). The publication count started low (around 1—5 per year in the late 1980s) and experienced significant acceleration, reaching the maximum of 60 publications in 2023, before showing a sharp drop in 2025. The

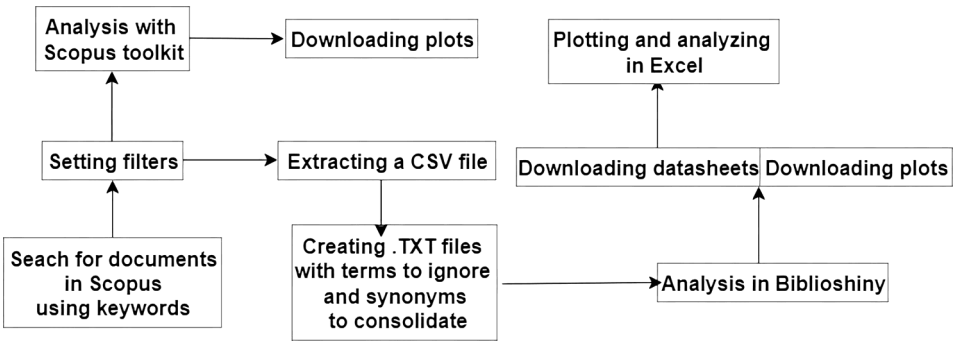


Fig. 1. Study flowchart

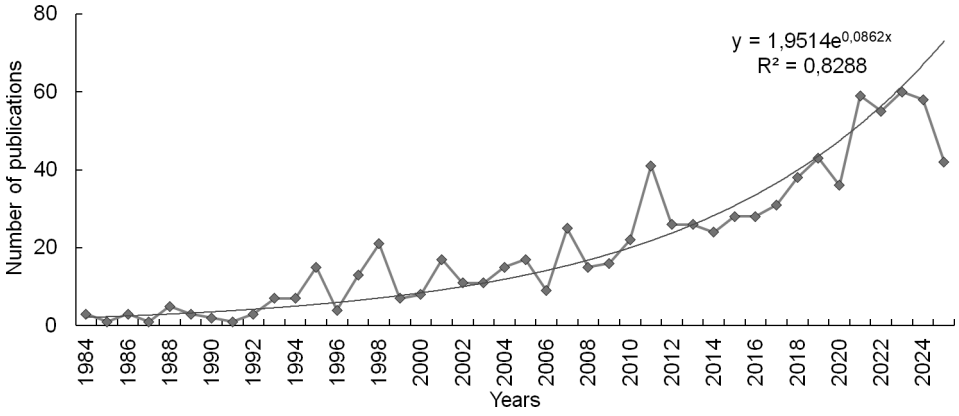


Fig. 2. Annual distribution of publications in the 'drought in durum wheat'-related research (Scopus dataset)

data for 2025 is still immature and hence inconclusive. Such a highly volatile growth pattern may be explained by year-to-year weather fluctuations: it is natural that dry years provided more convenient conditions to investigate drought effects, select resilient cultivars, and accumulate more data to be published; hence, peaks in the temporal evolution of the number of publications are expected after such years. Indeed, for example, the 2011 peak was preceded by severe droughts in Middle East and Central Asia in 2008/2009 [44], in Tunisia (one of the top durum wheat producers) in 2010/2011 [45], and in the Mediterranean Basin in 2008/2009 and 2010/2011 [46]. However, this explanation is not overarching and this assumption needs further verification. Other factors may influence the time profile of the publishing activities.

We used an exponential growth model, which suggests that the rate of publication production is accelerating over time. In this model, the exponent coefficient is 0.08228, meaning that an approximate annual growth rate of 8.23 % in the number of publications over the entire period. The coefficient of determination, R^2, is used to quantify the fit of a trend line to observed data. In our model, the R^2 of 0.86051 means that approximately 86.05 % of the variation in the annual number of publications (y) is explained by the passage of time (x). This rather high value suggests a strong correlation and indicates that the trendline, which represents changes in publication numbers over the analysed timespan, closely aligns with the real data, reflecting a significant and steady increase in the number of publications related to drought and durum wheat over the studied period. The temporal evolution of research themes is discussed below.

The citation patterns look different. Mean total count of citations per article reflects the long-term impact and accumulation of citations for a cohort of papers. Fig. 3 illustrates the temporal evolution of this parameter in durum wheat and drought research. The most prominent feature is an extremely high initial peak (mean citations per article 882; mean citations per year 18.4) in 1978. This peak is attributed to the paper [Fischer, R.A. & Maurer, R. (1978). Drought resistance in spring wheat cultivars. I. Grain yield responses. Australian Journal of Agricultural Research, 29(5), pp. 897-912. https://doi.org/10.1071/AR9780897], with the total citation

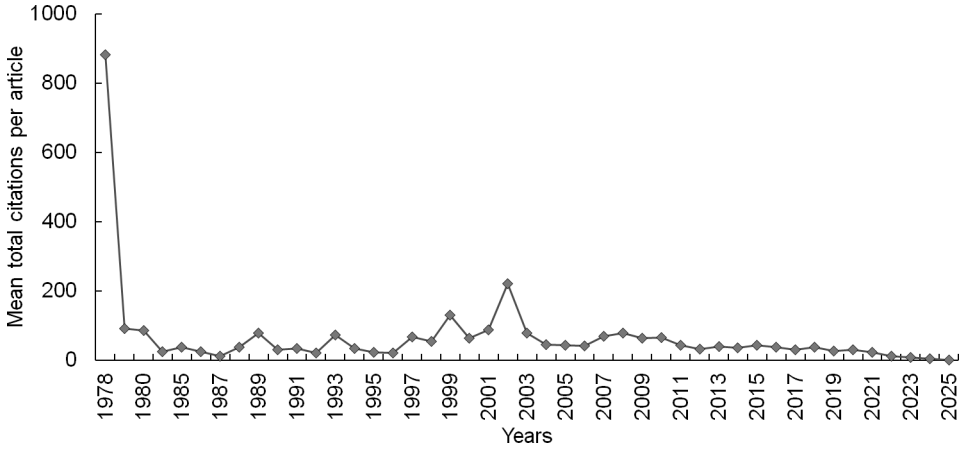


Fig. 3. Temporal evolution in mean total citation per article in the 'drought in durum wheat'-related research (Scopus dataset)

count of 1,756. It is followed by a general long-term decline until 2002, when another, less prominent peak is seen. The mean total citations per article generally decrease over the last two decades. Such declines are usually attributed to the varying quality of article contents and the timing of their publication [47, 48], i.e. the decline seen in this graph suggests that newer papers are accumulating fewer citations over their lifespan compared to older papers. As to correlation between publication quality and citation count, relationships are more complicated. Most of the comparative studies found a moderately positive correspondence but the correlations were far from perfect and there were great inter-study variations in the assessment results [49].

Mean total count of citations per year is a measure of the citation velocity or short-term impact**.** Unlike the graph in Fig. 3, the mean total citations per year (Fig. 4) exhibit more stability. Analysis in Biblioshiny allowed us to distinguish 10 top (by number of publications) countries in durum wheat and drought research, which were ranked as follows: Italy

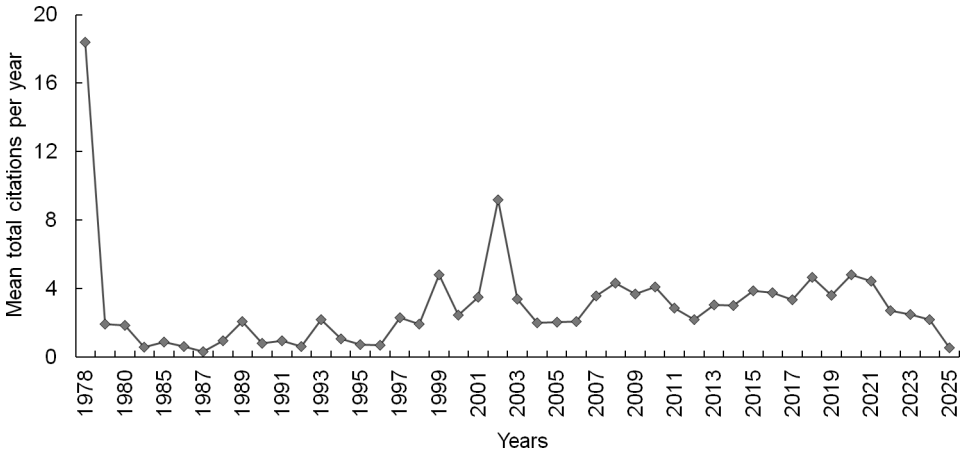


Fig. 4. Temporal evolution in mean total citation per year in the 'drought in durum wheat'-related research (Scopus dataset)

(871) > Iran (305) > Spain (300) > Tunisia (261) > Morocco (218) > Algeria (195) > Australia (143) > France (143) > USA (118) > Lebanon (116). We also identified 10 most prolific affiliations, which were also placed in the descending order: Islamic Azad University (114 publications) > Universitat de Barcelona (111) > International Center for Agricultural Research in the Dry Areas Syria (108) > University of Carthage (99) > Centro Internacional de Mejoramiento de Maiz y Trigo (79) > Universita Degli Studi Della Tuscia Viterbo (65) > Alma Mater Studiorum Universita Di Bologna (55) > Centre de Biotechnologie de Sfax (55) > University of Sfax (49) > The University of Queensland (47).

The three-field plot (Sankey diagram) in Fig. 5 visualizes the relationships between author country (AU_CO), author affiliation (AU_UN), and individual authors (AU) within the Scopus dataset. The height of each bar corresponds to the number of publications. Australia, Tunisia, Spain, France, Italy, Algeria, Morocco, USA, Lebanon, and Iran are present on the left, which agreed with the previous analysis. The list of institutions is also in agreement with the above ranking. The flow of the connections (represented by the grey streams) indicates the strength and direction of collaborations and affiliations. For example, the University of Carthage is a Tunisian institution; however, we can observe the intensity of the relationship between University of Carthage and the other nine top countries. The thickness of the grey streams connecting a university to a specific

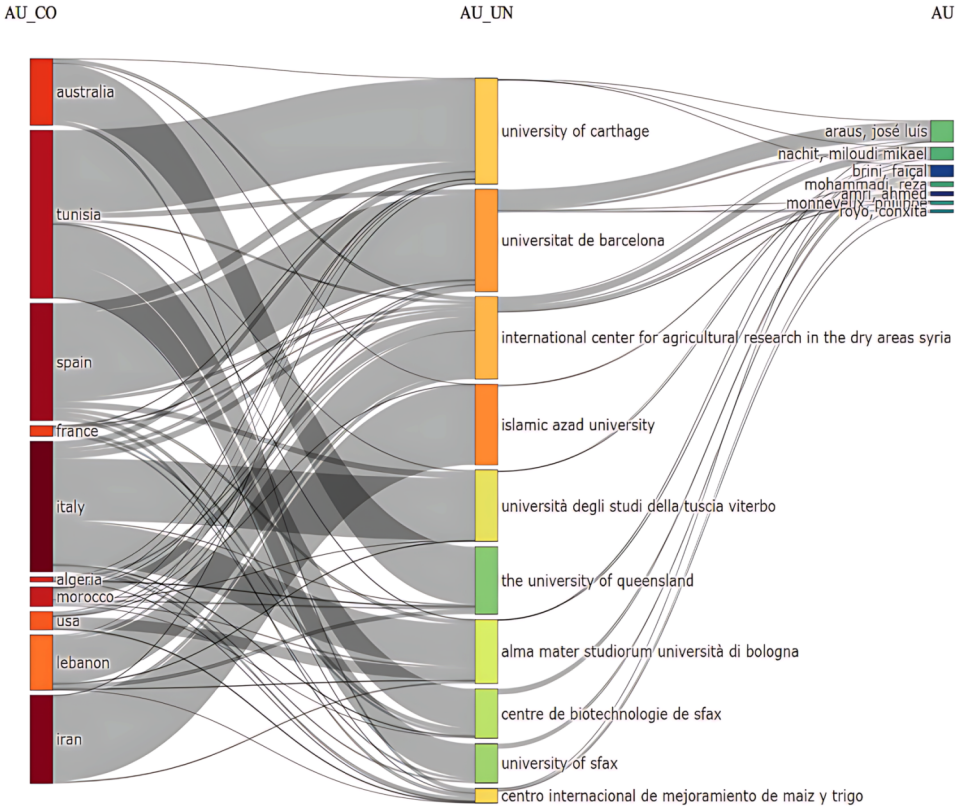


Fig. 5. Three-field plot of 10 top countries, affiliations, and authors in the 'drought in durum wheat'-related research (Scopus dataset)

author indicates the number of publications attributed to that author at that institution. For example, Araus J.L. (the most relevant author, see below) is primarily affiliated with Universitat de Barcelona, but he also conducts joint studies with 4 other institutions, specifically University of Carthage (Tunisia), International Center for Agricultural Research in the Dry Areas Syria, Alma Mater Studiorum Universita Di Bologna (Italy), and Centro Internacional de Mejoramiento de Maiz y Trigo (Mexico).

From the Scopus dataset, a total of 2,594 authors contributed to 865 publications on impact of aridity on durum wheat. Table 1 ranks 10 top authors by prolificity (number of publications) and influence (citations). It is obvious that the most prolific authors are not necessarily the most cited ones. The publication number-based and H-index (Hirsch index)-based rankings are generally in good agreement, though not identical. It is the most popular index, as it measures the volume and quality balance. However, it has certain limitation, as it ignores the exact number of citations for highly-cited papers and is career-length dependent (older researchers naturally have higher H-indices). To obtain a more complete picture, we also analysed G-index (Egghe-index) and M-index (M-Quotient). The G-index is the same as or higher than the H-index because G-index allows citations from the most-cited papers to "reinforce" the lower-cited papers. As a result, in our study, the publication number-based and G-index-based rankings of the 10 top authors were identical. Unlike measures of citation weight, the M-index is a normalization metric. M-index measures the annual rate of increase of the H-index. It allows for a fairer comparison between young and senior researchers. In our case, the M-index brought a lot of new names to the list of top authors.

TABLE 1. Most prolific and influential authors in the 'drought in durum wheat'-related research (Scopus dataset)

No	Authors	Articles	Author	H-index	Author	G-index	Author	M-index
1	Araus J.L.	32	Araus J.L.	24	Araus J.L.	32	Licaj I.	1.333
2	Nachit M.M.	30	Nachit M.M.	21	Nachit M.M.	30	Rocco M.	1.333
3	Mohammadi R.	28	Royo C.	19	Mohammadi R.	26	Barro F.	1
4	Monneveux P.	21	Monneveux P.	16	Monneveux P.	21	Di Meo M.C.	1
5	Royo C.	20	Mohammadi R.	13	Royo C.	20	Fiorillo A.	1
6	Huseynova I.M.	17	Garcia-del-Moral L.F.	12	Huseynova I.M.	17	Marin-Sanz M.	1
7	Di Fonzo N.	16	Brini F.	11	Di Fonzo N.	16	Meddich A.	1
8	Brini F.	15	Di Fonzo N.	11	Brini F.	15	Quagliata G.	1
9	Amri A.	14	Flagella Z.	11	Amri A.	14	Pisante M.	1
10	Merah O.	14	Maccaferri M.	11	Merah O.	14	Varricchio E.	1

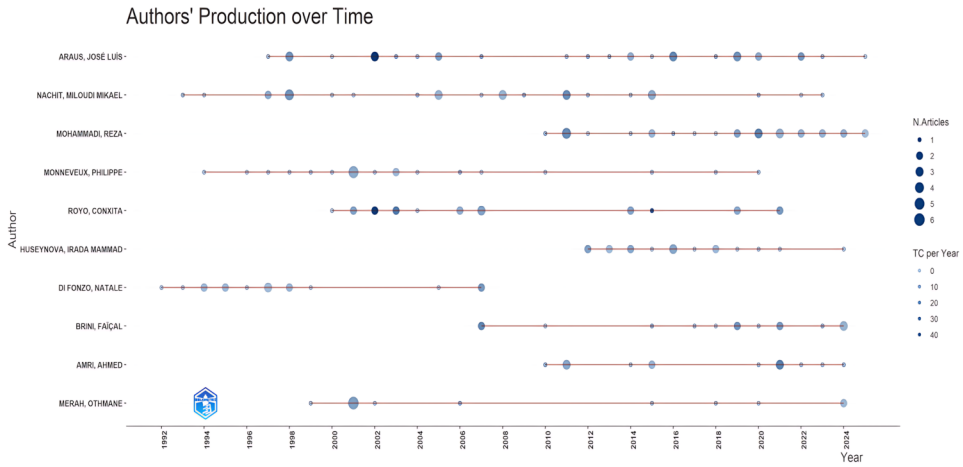


Fig. 6. Temporal trends in the top researchers' activities in the 'drought in durum wheat'-related research (Scopus dataset)

The plot in Fig. 6 highlights diverse researchers' trajectories. The bubble size corresponds to the number of articles, while the colour intensity reflects citations per year. Some authors show a longer and more consistent publishing history, while others appear to have more recent or focused periods of activities. Araus J.L. has a long and sustained publication record, starting around 2000 and continuing to the present. There is an early period with high productivity and high citation (around 2002), suggesting an early influence on the field. Nachit M.M. is also visualized with a long publishing timeline. Publications appear more concentrated around 2010—2015. Mohammadi R. showed a more recent burst of activity, starting around 2010, and at least some of his works are rather highly cited. Monneveux P. has a long publication record, but without highly influential papers. Royo C.: her timeline shows a strong presence in the early 2000s and then again in the mid-2010s, with some papers having high citation rates. Compared to other top authors, Huseynova I.M. has a relatively short publication record, which has started mainly since 2012 and has no highly cited articles so far. Di Fonzo N. appears to have been active until 2007. Brini F. activities were concentrated in two periods, around 2007 and then again more recently. His articles can be classified as moderately cited. Amri A. has launched his publication record since 2010 and became active again in the early 2020s, with moderately cited publications too. Merah O. has earlier publications around 2000 and more recent publications after 2010, which has not gained high citation counts.

Table 2 shows 10 most relevant journals by number of publications and by H-index. In general, these lists are similar. Such journals as Euphytica, Frontiers in Plant Science, Agronomy, and International Journal of Molecular Sciences are almost equally important in terms of both bibliometrical parameters. Nevertheless, Plant Physiology and Biochemistry, eighth ranking journal by number of publications, is not among 10 top journals distinguished by H-index and, vice versa, Plant Science, sixth ranking journal by H-index impact, is not included in the top ten based on number of publications.

TABLE 2. Most relevant sources in the 'drought in durum wheat'-related research (Scopus dataset)

No	Sources	Number of articles	Sources	H-index
1	Cereal Research Communications	32	Frontiers in Plant Science	19
2	Frontiers in Plant Science	32	Euphytica	18
3	Euphytica	25	Field Crops Research	16
4	Agronomy	23	Agronomy	13
5	Field Crops Research	19	European Journal of Agronomy	13
6	Plants	18	Plant Science	13
7	European Journal of Agronomy	17	Cereal Research Communications	12
8	Plant Physiology and Biochemistry	16	International Journal of Molecular Sciences	11
9	International Journal of Molecular Sciences	15	Journal of Experimental Botany	10
10	Journal of Agronomy and Crop Science	13	Journal of Plant Physiology	10

'Trend Topics' plots facilitate a visual analysis and projection of research focal points. Quartiles, or time periods, are used to segment the data and show when these topics emerged or became more prominent. Circles denote median years. The emergence of keywords like "yield" and "water stress" from 2003 (year (Q1)) and 2006 to 2020 (year (Q3)) and 2021, respectively, with the medians in 2014 and 2015 and the term frequencies of 50 and 105, respectively, suggests that they are of persistent research interests (Fig. 7). The relatively recent appearance of terms such as "climate change" (year (Q1) — 2017; year (Q3) — 2022, median year — 2020; term frequency — 51), "abiotic stress" (year (Q1) — 2016; year

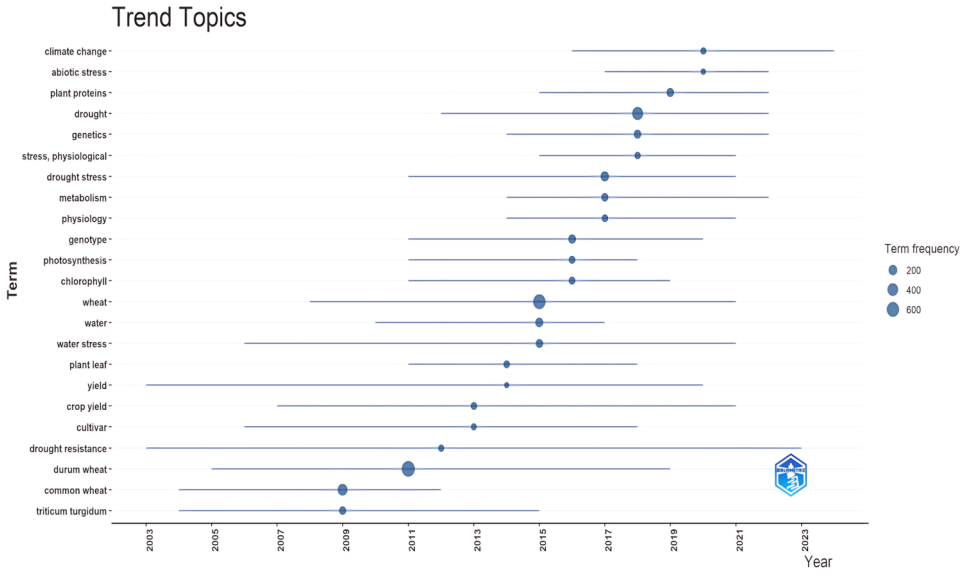


Fig. 7. Theme trajectories based on authors' keywords in the 'drought in durum wheat'-related research (Scopus dataset) (word minimum frequency — 50; number of words per year — 3)

(Q3) — 2021; median year — 2020; term frequency — 62), "physiological stress" (year (Q1) — 2015; year (Q3) — 2024; median year — 2018; term frequency — 65), and "plant proteins" (year (Q1) — 2015; year (Q3) — 2022; median year — 2019; term frequency — 119) indicates their likelihood as future research directions. At the same time, the term "common wheat" (year (Q1) — 2004; year (Q3) — 2012, median year — 2009) disappeared from the research related to impact of drought on durum wheat plants, despite its high frequency of 285. This may be due to the fact that recent studies tend to concentrate rather on *T. durum* than on related species, as at least some of mechanisms of resistance can species-specific or even cultivar-specific.

Fig. 8 gives more insights into the temporal evolution of research mainstreams in the durum wheat and aridity problematics by 1984. There are only two clusters, with few nodes, in the time slice for 1984. "Drought tolerance" is its own cluster, while "salinity", "germination", and "photosynthesis" are in the same cluster with wheat. The big size of the photosynthesis node can be pre-eminently explained by technological breakthroughs. By 1984, the first reliable commercial infrared gas analysers (for example, in 1969, The Analytical Development Company Limited, one of the first and leading companies manufacturing equipment for photosynthesis performance evaluation, was founded [50]) and radiocarbon techniques [51] had been widely introduced into the practice of plant physiologists. Farquhar and Sharkey published a seminal article on association between stomatal conductance, photosynthetic performance and stress [52]. As to salinity, the conceptual approach of uniting different types of stresses under the umbrella of "osmotic stress" dominated: both drought (water deficit) and salinity act on the plant in a similar way — they lower the osmotic potential of the soil solution, preventing the roots from absorbing water ("physiological dryness"). By the end of the 1970s, humanity was faced with a catastrophic consequence of mass irrigation in arid regions — secondary soil salinization [53]. Since durum wheat is historically a crop of these semi-arid zones, the study of its photosynthesis under salinity conditions became the main trend in agronomic science at that time. At that time, research heavily relied on macro-phenotypic screening methods. Germination rate was (and still is) a simple but reliable criterion of crop resilience.

During the next decade, the red cluster was significantly expanded: "yield" and "biomass" (accumulation) were added as criteria of resilience (Fig. 9). Breeding for drought resilience showed massive achievements, making "breeding" one of the most frequently used keywords. Logically, "genetic variations" in the context of breeding for drought resistance and investigating its mechanisms were another focus of studies [54]. Instead of general ecological descriptions, the literature was increasingly using the



Fig. 8. Bibliometric map of author keyword clustering for drought-related research in durum wheat (1984; Scopus dataset). The same clustering settings are used for Figures 9-12

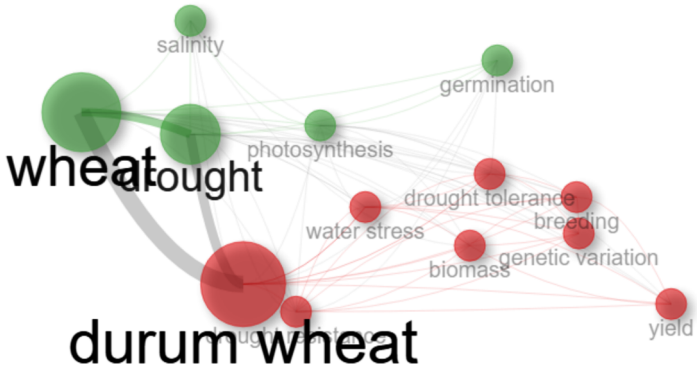


Fig. 9. Bibliometric map of author keyword clustering for drought-related research in durum wheat (1994; Scopus dataset)

term "water stress", which was measured through very specific indicators: relative water content and leaf water potential [55]. During the 1984—1994 period, "drought tolerance" and "drought resistance" appeared within the same thematic cluster but exhibited a substantial spatial distance from each other. Bibliometrically, this separation reflects a clear focus on distinct physiological mechanisms of adaptation as conceptualized by Levitt [56].

Drought resistance is the overarching, umbrella term for how a plant survives water scarcity, whereas drought tolerance is a specific, underlying mechanism that allows plant cells to function even when dehydrated. Drought resistance encompasses all strategies a plant uses to survive, recover, and reproduce during periods of water deficit. It includes three primary mechanisms: 1) Drought escape. The plant rapidly completes its life cycle before a severe drought sets in [57]. 2) Drought avoidance. The plant avoids internal dehydration by either developing deep roots to find groundwater [58] or reducing water loss due to cuticular wax [59], through leaf shedding [60] and stomatal closure [61]. 3) Drought tolerance. Surviving tissue dehydration without suffering lethal damage through specific cellular defence mechanisms, e.g. dehydrins [62] and late embryogenesis abundant (LEA) proteins [63] acting as "molecular shields" that protect cells from dehydration, QTL/genes linked with cell membrane stability [64], osmotic adjustment [65], biochemical protection of the photosynthetic apparatus [66]. Agronomists and plant breeders predominantly employ "drought resistance" to evaluate field performance and yield stability, whereas plant physiologists and biochemists focus on "drought tolerance" to describe cellular-level survival mechanisms. It may explain why these terms rarely co-occurred in the same experimental contexts, leading to their spatial divergence in our map.

The 1995—2004 decade gave birth to a new (blue) cluster (Fig. 10). This cluster drew a part of the salinity topic on itself, as evidenced by "salt stress" as a new dominant keyword. The emergence of the term "salt stress" marks the transition of science to the molecular, cellular and genetic levels [67]. The green cluster, with keywords such as "germination", "drought", "phenotype", "salinity", "water", etc., is rather whole plant-oriented than centred on molecular mechanisms of plants' resilience and

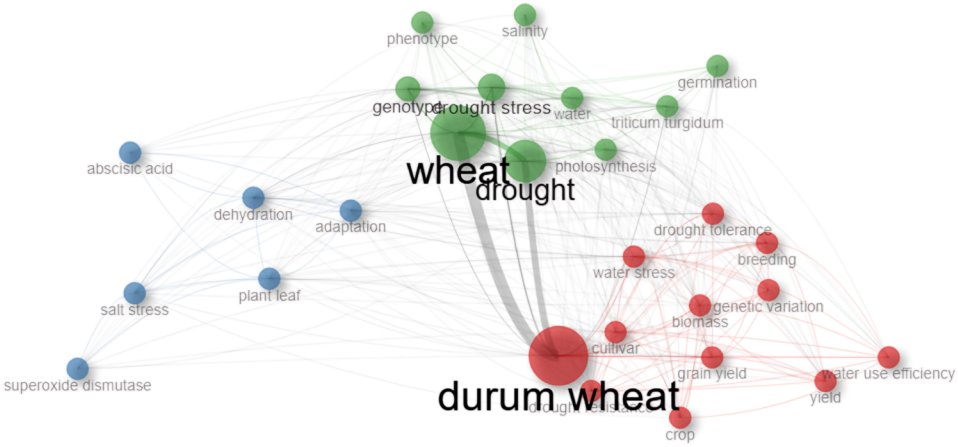


Fig. 10. Bibliometric map of author keyword clustering for drought-related research in durum wheat (2004; Scopus dataset)

tends to contain terms describing environment, while the blue cluster includes keywords concerning the condition of the plant itself (salinity is a soil characteristic, while salt stress concerns the plant organism). It also includes the first "biochemical" keywords: "abscisic acid" and "superoxide dismutase". This confirms that during this decade, triticologists moved from simple observations of drought effects to research into signal transduction, with abscisic acid (ABA) emerging as the undisputed "stress hormone" [68]. This period marked a massive realisation in plant science: both drought and salt stress inevitably induce a dangerous secondary stress — oxidative stress. When stomata close and CO_2 is restricted, the excess light energy absorbed by chlorophyll overloads the electron transport chain. This leads to the explosive generation of toxic reactive oxygen species (ROS), such as superoxide radicals ($O_2^{\bullet-}$).

Superoxide dismutase (SOD) is the first line of enzymatic defence, dismutating $O_2^{\bullet-}$ into less harmful hydrogen peroxide. Between 1995 and 2004, measuring SOD activity became the standard benchmark to prove whether a specific wheat genotype possessed biochemical resilience [69]. The other keywords in the blue cluster include "dehydration", "adaptation", and "plant leaf". In plant physiology, "drought" is a macro-environmental condition (dry soil/air), whereas "dehydration" describes the actual physical loss of water from intracellular spaces. Hence, the scientific community focused heavily on dehydration tolerance mechanisms [70, 71]. Rather than just observing passive damage, studies in this cluster investigated active adaptation (osmotic adjustment, upregulation of the antioxidant system) to allow the plant to survive and thrive under prolonged stress [71]. While the other clusters looked at broad parameters like grain yield, biomass, phenotype, the "biochemical" cluster investigated extensively the leaf, where the most volatile stress consequences happen: it's the site of photosynthesis, stomatal control, ABA accumulation, and the primary victim of ROS-driven oxidative stress.

The distribution of "water stress", "drought stress", and "salt stress" into different clusters may reflect the functional differentiation of research

paradigms within durum wheat literature. Water stress is centrally linked to breeding and agronomy; hence, this term is linked with “grain yield”, “biomass”, “crop”, “cultivar”, etc.). Drought stress operates as the overarching ecological framework, connecting whole-plant phenotypic outcomes (“germination”, “phenotype”) with environmental conditions. Salt stress functions as a laboratory-based experimental tool. Thus, our bibliometric network successfully maps the disciplinary divide between field-based agronomic evaluation and laboratory-based molecular physiology.

It was at the turn of the 1990s and 2000s that a large-scale movement began in the world to expand the genetic pool of durum wheat [72]. This explains the emergence of “*Triticum turgidum*” as a top keyword (green cluster). The appearance of “water use efficiency” (WUE) in the red cluster (for convenience, let us call it “breeding/agronomic” cluster) during the 1994—2004 period reflects that WUE transitioned from being a purely physiological parameter to becoming a primary target for cereal breeding [73].

During the 2005—2014 decade, the blue cluster underwent a significant thematic evolution, with the emergence of “gene expression regulation” as central nodes (Fig. 11). This shift captures the molecular-genetic turn in durum wheat research, where the focus transitioned from descriptive biochemical profiling to unravelling the transcriptional networks that orchestrate stress resilience. Researchers increasingly targeted the transcriptional control of adaptive pathways, focusing on how transcription factors (e.g., DREB, WRKY) regulate the complex responses to stress at the genomic level [74—77]. In this decade, the expansion of the blue cluster to include “growth, development, and ageing” signifies a transition toward an integrated view of plant life cycle strategies under stress. This period emphasized that stress-responsive gene expression is not merely a reactive defence but a regulatory mechanism that recalibrates the plant’s developmental program. Researchers focused on the genetic and molecular basis of stress-induced senescence [78]. The linkage between “gene expression regulation” and developmental traits reflects the discovery of key regulators that man-

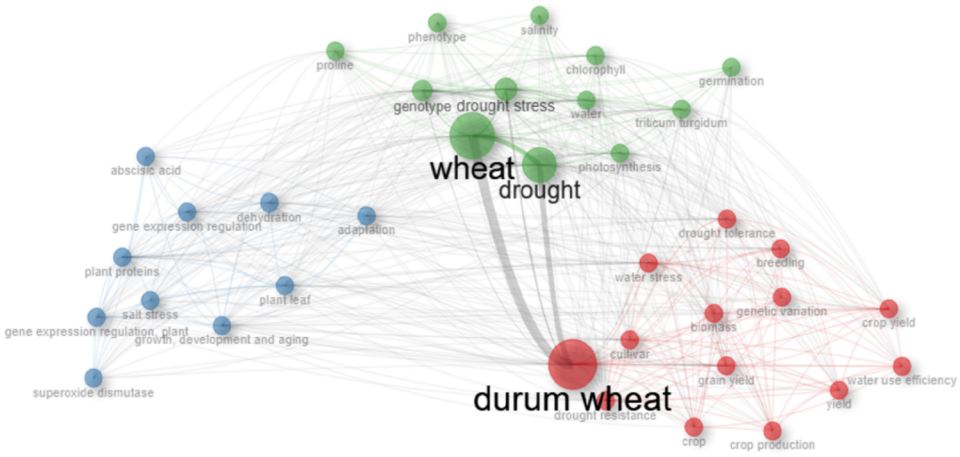


Fig. 11. Bibliometric map of author keyword clustering for drought-related research in durum wheat (2014; Scopus dataset)

age the trade-off between growth and survival, allowing the plant to prioritize reproductive fitness at the expense of vegetative development [79].

With the development of biochemical assays, “proline”, a ubiquitous osmoregulatory metabolite, emerges as another top keyword. We could expect its appearance in the “biochemical/genetic” blue cluster, but the proline node is located in the green cluster, though having lots of links to blue nodes. In this context, “proline” can be considered as a bridging node between the green (“whole-plant”) and blue clusters. This position reflects its dual utility in durum wheat research: on one hand, it serves as a robust physiological marker for phenotypic screening under drought and salinity within the green cluster, where researchers correlate its accumulation with stress-adaptive phenotypes. On the other hand, its strong connectivity to the blue cluster highlights its role as a downstream metabolite of the stress-responsive gene expression regulation pathways [80—82].

During the 2015—2024 decade, the blue cluster seems to have evolved from a “narrow molecular focus” to a large integrative system (Fig. 12). The emergence of words like “metabolism”, “genetics”, “physiology”, “antioxidants” (rather than narrow terms like ascorbic acid, glutathione, carotenoids, or phenolic compounds), proteins (rather than dehydrins or LEA proteins) suggests that in the last 10 years the research has moved to systems biology. The emergence of “controlled study” indicates that science has become more rigorous in terms of methodology (for example, due to reproducibility requirements in high-ranked journals). In addition to “plant leaf”, “plant root” has become one of the main objects in studies of wheat resistance to drought [83, 84]. The appearance of “sodium chloride” in the blue cluster can be attributed to the fact that in agricultural research, NaCl is still widely used to experimentally simulate osmotic drought stress [85, 86]. Interestingly, while “sodium chloride” appears as a distinct blue node — largely due to its dual role as both an osmotic stress agent and a primary focus of salt-tolerance studies — “polyethylene glycol” (PEG), another osmotic agent used to simulate drought conditions, remains absent from the keyword network. This discrepancy can illustrate

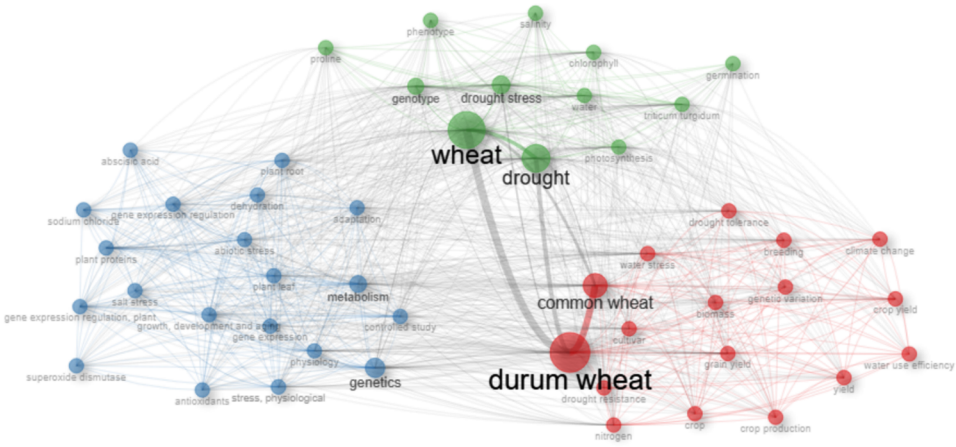


Fig. 12. Bibliometric map of author keyword clustering for drought-related research in durum wheat (2024; Scopus dataset)

a common trend in scientific indexing: technical reagents used for stress simulation, such as PEG, are frequently confined to the methodology sections and rarely prioritized as formal keywords.

The green cluster contains a new keyword — "chlorophyll". Although from a biochemical perspective chlorophyll is an integral part of metabolism and is expected to be in the blue cluster, in this bibliometric space it is located in the "whole plant" cluster. This reflects its utilitarian role in modern science: chlorophyll has become a major phenotyping tool. Its distance from molecular (blue) nodes may highlight the methodological gap between fundamental studies of gene expression mechanisms and applied field studies, where chlorophyll serves as a rapid indicator for assessing the adaptive status of large groups of genotypes (using SPAD-meters, Normalized Difference Vegetation Index) [87, 88]. There are also new nodes in the red cluster: "common wheat" and "nitrogen". The common wheat circle is rather big, indicating a great portion of comparative studies on different wheat species. Here, one may see a contradiction with the trend topics visualised in Fig. 7. However, this contradiction is more apparent than real. Trend topics charts reflect the total number of studies where the keyword appears, while co-occurrence maps visualise links between top keywords. The trend topics chart in Fig. 7 shows that there were lots of publications with common wheat as a keyword, but their quantity declined after 2012. The absence of "common wheat" in the 2014 (Fig. 11) map means that this term had no significant links with other top keywords in that period. The rather big circle of common wheat in the 2024 map reflects the emergence of sustainable links between this term and others red nodes, despite the fact that there were fewer papers with common wheat as a keyword after 2012. The emergence of "nitrogen" in the red cluster of the 2024 map may be associated both with nitrogen use efficiency as a state-of-the-art criterion of drought resistance on one hand [89] and with usage of nitrogen fertilizers to mitigate consequences of drought stress on the other hand [90].

One might have expected "thermal stress" or "heat tolerance" to emerge as significant nodes, given that drought and high temperature are typically concurrent stressors in rainfed systems [91]. Furthermore, the concept of cross-resistance — where plant genotypes exhibit integrated responses to multiple abiotic factors — is well-documented in recent literature [92]. However, these specific terms do not appear as distinct nodes in our co-occurrence maps. This is likely because these aspects are integrated under the broader umbrella term "abiotic stress", which serves as a blue node in the 2024 network. Thus, the bibliometric clustering suggests that "abiotic stress" acts as a hierarchical keyword, subsuming specific stress-related terminology and reflecting a systemic research focus on complex environmental challenges. In similar manner, "photosynthesis" is likely to cover papers on drought-inflicted changes in thylakoids [93] and Rubisco activity [4].

The top most-cited articles (with total citation count of > 200) were selected for a focused bibliometric analysis to determine their influence on the development of research in the analysed area. According to the content of these papers (Table 3), the 'response of durum wheat to drought'-

TABLE 3. Most cited articles in the 'drought in durum wheat'-related research (Scopus dataset)

No	Paper	Total citations	Theme	Major findings
1	[94]	1,756	Effect of drought on yield; comparison of durum wheat with other cereals	Durum wheat cultivars were the most susceptible to drought.
2	[104]	1,008	Physiological traits that contribute to improved productivity under mild to moderate drought	Useful features: phenological traits increasing amounts of water used during grain filling, or adjusting the crop cycle to seasonal patterns of rainfall; augmented contribution of carbohydrate reserves accumulated during vegetative growth to grain filling.
3	[99]	739	Modification of an electrolyte leakage technique for evaluation the cell membrane stability as a mechanism of water stress tolerance in durum wheat	The proportions of lost endogenous ions varied strongly according to the element analysed. An increase in inorganic ion leakage did not fully explain the PEG-induced increase in electrical conductivity.
4	[100]	522	Roles of antioxidant system and pigments in drought resilience of durum wheat; effects of drought on photosynthesis	There was a significant increase in glutathione reductase and hydrogen peroxide-glutathione peroxidase activities, a decline in chlorophyll *a*, lutein, neoxanthin, and β-carotene contents, and an increase in the pool of de-epoxidized xanthophyll-cycle components only in the more drought-susceptible cultivar.
5	[98]	498	Effects of ionic toxicity and osmotic component of salt stress on germination in durum wheat	The main effect of PEG (osmotic component) occurred via an inhibition of water uptake, while detrimental effects of NaCl were likely to be linked to long-term effects of accumulated toxic ions. The behavior of cultivars during germination did not fully reflect their stress resistance in the field and, therefore, is not recommended as a reliable selection criterion for breeding.
6	[97]	375	Validity of laboratory screening tests to discriminate among cultivars differing in adaptation to the Mediterranean climate	Appropriately standardized tests could be possible tools in breeding programs for tolerance to heat and drought stresses.
7	[109]	374	Search for sources of adaptation to drought and heat	Wheat landraces stored in gene banks with highly beneficial untapped diversity and sources of stress adaptation should be used for wheat improvement. Unified development of databases and promotion of data sharing among researchers and breeders will greatly benefit wheat improvement.
8	[108]	341	Molecular mechanisms of response to drought shock in wild emmer	13 miRNAs were found to be differentially regulated in response to drought shock in the ancestor of durum wheat.
9	[107]	324	Genetic mechanisms of durum wheat adaptation to various water availability	2 quantitative trait loci had consistent effects on grain yield, heading date, and plant height across different environments.
10	[96]	296	Effects of temperature and moisture regimes on durum wheat yield and its components	Correlation analysis did not show clear associations. Path analysis appeared to be more informative. At higher temperatures, both under irrigated and rainfed conditions, negative effects of the number of spikes per square meter were registered on grain yield.

TABLE 3 (ending)

No	Paper	Total citations	Theme	Major findings
11	[110]	278	Review on ways to deal with the climate change challenge	Plant breeding has addressed both abiotic and biotic stresses. Strategies of adaptation to climate changes include matching of phenology to moisture availability, using photoperiod-temperature response, assortment of cultivars able to escape or avoid stresses at critical periods, improved water use efficiency and a re-emphasis on population breeding, specifically evolutionary participatory breeding, to provide a buffer against rising unpredictability.
12	[102]	247	Osmotic adjustment of durum wheat leaves to water stress	Water potential and relative water content decreased and stomatal resistance were most pronouncedly increased in the drought tolerant cultivar. Water stress also increased sugar and proline concentrations and decreased nitrate levels. The osmotic adjustment was greater in growing than in expanded leaves, especially in the cultivars best adapted to aridity. Sugars were the main solutes that contributed to osmotic adjustment followed by proline and then quaternary ammonium compounds.
13	[103]	227	Effects of drought on yield and metabolism	Severe water stress reduced durum wheat grain yield as well as dry matter and nitrogen accumulation and remobilization during grain filling.
14	[95]	226	Associations between drought-affected yield and morpho-physiological traits	No trait had clearly desirable effects on yield that could be used in selection for increased yield under drought.
15	[106]	223	Genetic and biochemical mechanisms of resistance to drought and related abiotic stresses	*T. durum* dehydrin improved tolerance to salt and drought stresses in transgenic *Arabidopsis thaliana*.
16	[105]	213	*T. durum* grain carbon isotope discrimination (Δ) and yield under contrasting water regimes	Higher Δ-driven selection for increased durum wheat yield in the Mediterranean could be efficient only in wet years or under supplementary irrigation.
17	[101]	201	Role of antioxidant system in response of durum wheat to salt stress	Antioxidative enzyme activities and ascorbate and glutathione contents showed different patterns in response to salt stress, depending both on plant parts and levels of cultivars' drought susceptibility.

related research was found to include the following themes: 1) Effects of drought on durum wheat yield, morphological, physiological, and biochemical traits; 2) Comparison of responses to drought between durum wheat and other wheat species and cereals; 3) Physiological, biochemical and genetic mechanisms of resistance; 4) Studies of drought and other abiotic stresses; 5) Search for sources of adaptation to drought; 6) Ways to deal with the climate change challenge; 6) Search for traits that could drive breeding for drought resilience; 7) Making use of different strategies of drought resistance (drought escape, drought avoidance, and drought tolerance); 8) Development of methods to assess drought resilience and sus-

ceptibility. A shift in the focus of studies should be noted: earlier studies just assessed how much yield was affected by drought and investigated what morpho-physiological traits could be associated with stable yields under drought [94—96] and tried different tests to predict tolerance of crops to drought [97—100]. Then the accent gradually started to be made on physiological and biochemical changes induced by drought and on systems that could determine resistance to or provide protection against drought [101—103]. Implications of physiological peculiarities for breeding were also reflected in highly influential publications [104, 105]. More recent studies discovered insights into genetic and molecular mechanisms of drought resistance [106—108] and breeding solutions to narrowed genetic diversity and climate change [109, 110].

Conclusions

A bibliometric analysis of articles in the Scopus database was conducted regarding response of durum wheat to drought. The Scopus dataset had 865 documents spanning the years 1946—2025. The distribution of the papers that have been indexed in the Scopus database was considered in terms of temporal and regional patterns, institutions, authors, keywords, and publications. Based on the investigation, Italy was identified as the greatest contributor among countries. Most relevant authors, journals and affiliations were distinguished. The keywords "yield" and "water stress" indicate areas of persistent research interests. The terms "climate change", "abiotic stress", "physiological stress", and "plant proteins" point to probable research directions in future. Review of the most-cited articles allowed us to outline major themes in the 'impact of drought on durum wheat'-related research, with a shift from assessing drought-inflicted reduction in yield to elucidation of molecular mechanisms of drought resistance.

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AI USE DECLARATION

During the preparation of this work, the authors used an AI-based language model (Gemini) for improving the English language, grammar, and academic style of the manuscript. After using this tool, the authors reviewed and edited the content as necessary and bear full responsibility for the content of the publication.

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БІБЛІОМЕТРИЧНИЙ АНАЛІЗ ДОСЛІДЖЕНЬ РЕАКЦІЙ ТВЕРДОЇ ПШЕНИЦІ НА ПОСУХУ: ВІД ПОЛЬОВИХ СПОСТЕРЕЖЕНЬ ДО СИСТЕМНОЇ БІОЛОГІЇ

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Проведено бібліометричний аналіз наукових досліджень проблеми впливу посухи на тверду пшеницю на основі даних бази Scopus. Вибірка охоплює корпус із 865 документів, опублікованих у період з 1946 по 2025 рік. Розглянуто часові та регіональні закономірності, визначено найважливіші установи, авторів, ключові слова та публікації. Згідно з моделлю експоненціального зростання, щорічний приріст кількості публікацій за весь період становив 8,23 % при коефіцієнті детермінації $R^2 = 0{,}86051$. Встановлено, що Італія є лідером за внеском у дослідження серед усіх країн. Для оцінки рейтингу авторів застосовано H-, G- та M-індекси. Визначено, що Frontiers in Plant Science є найважливішим журналом у цій галузі. За допомогою діаграми Санкі проаналізовано взаємозв'язки між країною автора, установою та окремими дослідниками. Розглянуто основні етапи еволюції ключових слів. Ключові слова «урожайність» (yield) та «водний стрес» (water stress) на діаграмі актуальних тем свідчать про сталі наукові інтереси. Терміни «зміна клімату» (climate change), «абіотичний

стрес» (abiotic stress), «фізіологічний стрес» (physiological stress) та «рослинні білки» (plant proteins) вказують на перспективні напрями подальших досліджень. Огляд найцитованіших статей окреслив основні теми літератури з адаптації твердої пшениці до посухи, продемонструвавши зміщення акцентів від оцінки втрат урожаю, спричинених посухою, до з'ясування молекулярних механізмів посухостійкості. Аналіз часових карт спільної появи ключових слів засвідчив зародження «біохімічного/генетичного» кластера, який згодом трансформувався у кластер «системної біології». Бібліометричне картографування ключових слів розглянуто крізь призму розвитку досліджень адаптації твердої пшениці до посухи. Виявлено найвпливовіші публікації та узагальнено їхні основні результати.

Ключові слова: *Triticum durum*, абіотичний стрес, аридність, Biblioshiny, наукові тренди, часові та регіональні закономірності, карти спільної появи.

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