



Water Productivity in Mediterranean Regions: A 2002–2025 Bibliometric Analysis

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Abstract

Water productivity, linking water use efficiency to crop yield, ecosystem sustainability, and climate resilience, is increasingly critical in Mediterranean regions facing severe water scarcity. This study presents a comprehensive bibliometric analysis of water productivity research from 2002 to 2025 using the Scopus database and VOSviewer network mapping. We analyzed publication trends, leading countries, institutions, authors, subject areas, keyword co-occurrence, and citation patterns among the most influential journals to reveal the intellectual structure and evolution of the field. Results show a steady increase in research output, with Spain, Italy, and as top contributors. Environmental and agricultural sciences dominate, reflecting the integration of hydrology, agronomy, and technological innovation. Three main thematic clusters emerged: (i) basin- and ecosystem-scale hydro-biogeochemical processes, (ii) crop-level physiological optimization under water stress, and (iii) soil water conservation and decision-support frameworks. Gaps remain in socio-economic integration, policy application, and smallholder inclusion, emphasizing the need for transdisciplinary, climate-adaptive strategies. This study provides a roadmap for sustainable water management and agricultural resilience in water-limited regions.

1. INTRODUCTION

Water productivity has emerged as a fundamental concept in environmental science, hydrology, and sustainable agricultural management, as it directly links water use efficiency with food production, ecosystem sustainability, and climate resilience. Increasing pressure on freshwater resources, driven by climate change, population growth, land degradation, and rising food demand, has intensified the need to optimize water use across sectors (FAO, 2020; WWAP, 2023). Agriculture accounts for nearly 70% of global freshwater withdrawals, making improvements in water productivity essential for achieving food security and sustainable development (FAO, 2017; Molden et al., 2010). In water-scarce regions, particularly Mediterranean environments,

enhancing productivity per unit of water has become a critical strategy to mitigate water scarcity while maintaining agricultural viability and ecological balance (Feres & Soriano, 2007; Pereira, Cordery, & Iacovides, 2012).

Water productivity is commonly defined as the ratio between agricultural output and water input, encompassing multiple dimensions including physical, economic, and environmental productivity (Zwart & Bastiaanssen, 2004; Molden, 2007). The concept has evolved from traditional irrigation efficiency metrics toward integrated frameworks that account for water consumption, evapotranspiration, and ecosystem services (Falkenmark & Rockström, 2006). Crop water productivity (CWP), which relates yield to evapotranspiration, remains one of the most widely used indicators for assessing

agricultural water performance (Steduto et al., 2012). In addition, water productivity assessments increasingly consider green and blue water components, reflecting the importance of rainfall and soil moisture in rainfed and mixed farming systems (Rockström et al., 2007; Schyns et al., 2019).

A wide range of methodologies has been developed to quantify and improve water productivity across spatial and temporal scales. Remote sensing has become a key tool for monitoring evapotranspiration, biomass production, and irrigation performance at regional and global levels (Anderson et al., 2012; Bastiaanssen et al., 2005; Senay et al., 2013). Satellite-based approaches enable the estimation of water productivity over large areas, particularly in data-scarce regions, and support water accounting initiatives and basin-scale planning (Karimi et al., 2013). In parallel, crop and hydrological models provide robust tools for analyzing water–yield relationships under varying climatic and management scenarios. The AquaCrop model, developed by FAO, simulates crop responses to water availability and has been widely applied in Mediterranean environments (Steduto et al., 2009; Raes et al., 2018; Raes et al. 2023; Busschaert et al. 2022; Salman et al., 2025)

Similarly, the Soil and Water Assessment Tool (SWAT) enables integrated assessments of hydrological processes and agricultural productivity at watershed scales (Arnold et al., 1998; Gassman et al., 2007). These modelling frameworks contribute to a deeper understanding of water–food–energy–ecosystem interactions and support evidence-based decision-making for sustainable water management (Falkenmark, Berntell, Jägerskog, Lundqvist, Matz, & Tropp, 2007). Recent advances in digital agriculture and climate-smart water management have further expanded the scope of water productivity research. Precision irrigation technologies, deficit irrigation strategies, and improved crop varieties have demonstrated significant potential to enhance productivity while reducing water consumption (Feres et al., 2011; Playán & Mateos, 2006, Raes et al., 2023 ; Busschaert et al., 2022 ; Salman et al. 2025). Moreover, integrated water management approaches that combine technological innovation with governance and policy frameworks are increasingly recognized as essential for improving water productivity at multiple scales (OECD, 2021; UN-Water, 2021).

These developments highlight the growing interdisciplinary nature of water productivity research, bridging agronomy, hydrology, remote sensing, economics, and environmental sciences.

To synthesize the expanding body of literature, bibliometric analysis has become an essential tool for mapping scientific progress and identifying research trends. Bibliometric methods enable the quantitative evaluation of publication patterns, collaboration networks, and thematic evolution within a research domain (Donthu et al., 2021; Aria & Cuccurullo, 2017). In the context of water productivity, bibliometric analyses provide valuable insights into dominant research themes, emerging topics, and geographical research distributions (Zhang et al., 2021). Such analyses are particularly useful for researchers and policymakers, as they facilitate the identification of knowledge gaps, innovation hotspots, and interdisciplinary linkages that shape the evolution of the field (Ellegaard & Wallin, 2015). Furthermore, they support the assessment of institutional contributions and international collaborations, offering a comprehensive overview of the global research landscape.

Previous reviews on water productivity have primarily focused on irrigation efficiency, crop modelling, and water-saving technologies at global and regional scales (Pereira et al., 2012; Molden et al., 2010). These studies highlight substantial progress in improving agricultural water use efficiency and adopting precision irrigation practices. However, many analyses remain fragmented, often emphasizing either technological innovations or specific geographic regions without fully integrating Mediterranean contexts, where water scarcity, land degradation, and climate variability strongly influence productivity outcomes (Feres et al., 2011; Iglesias & Garrote, 2015). Additionally, limited attention has been given to the evolution of research networks, thematic priorities, and methodological shifts within water productivity studies, particularly in regions facing acute water stress.

This study aims to conduct a comprehensive bibliometric analysis of scientific publications on water productivity in Mediterranean regions from 2002 to 2025. The analysis considers diverse methodological approaches, including CWP metrics, remote sensing-based assessments, and integrated hydrological modelling frameworks. It examines the temporal evolution of research output, identifies leading

countries, institutions, and authors, and classifies the dominant research themes to support future scientific directions. By providing a systematic overview of knowledge development, this study contributes to identifying research gaps, emerging priorities, and opportunities for innovation in water productivity science. Such insights are essential for guiding sustainable water management strategies, supporting climate adaptation efforts, and strengthening resilience in regions facing increasing water scarcity and environmental pressures.

2. METHODOLOGY

This study utilizes the Scopus database as the primary search platform, selected because it is one of the most extensive and comprehensive academic resources (Schotten et al., 2017; Pranckutė et al., 2021). Notably, Scopus integrates advanced indexing and analytical features that facilitate large-scale bibliometric investigations (Kipper et al., 2020).

The methodological framework for this research unfolds in five stages: defining search criteria, selecting the database, data collection, bibliometric analysis, and results interpretation, as illustrated in Fig. 1. To explore the evolution of water productivity research in Mediterranean regions, a conventional bibliometric approach was adopted, incorporating co-occurrence and network analysis techniques. VOSviewer

software, developed by Van Eck and Waltman, was employed as the primary visualization tool for constructing and mapping bibliometric networks (Van Eck et al., 2010). This software enables the identification of intellectual structures and thematic clusters through graphical representations of relationships among authors, institutions, keywords, and journals (Van Eck et al., 2010; Montalván-Burbano et al., 2020). Its application provided a comprehensive framework for revealing scientific patterns and collaboration dynamics within the water productivity research landscape.

In the initial phase of the study, specific search criteria were defined to guide the bibliometric exploration. The search strategy focused on keywords related to water productivity and its associated methodologies, including: “water productivity”, “crop water productivity”, “water use efficiency”, “irrigation efficiency”, “evapotranspiration”, “SWAT”, “remote sensing”, “water accounting”, and “Mediterranean region”. These keywords were selected to capture both conceptual and methodological dimensions of water productivity research. The search query was applied to titles, abstracts, and keywords to ensure comprehensive coverage of relevant literature.

Subsequently, the Scopus database was selected as the primary source for retrieving peer-reviewed publications. In the third stage, a

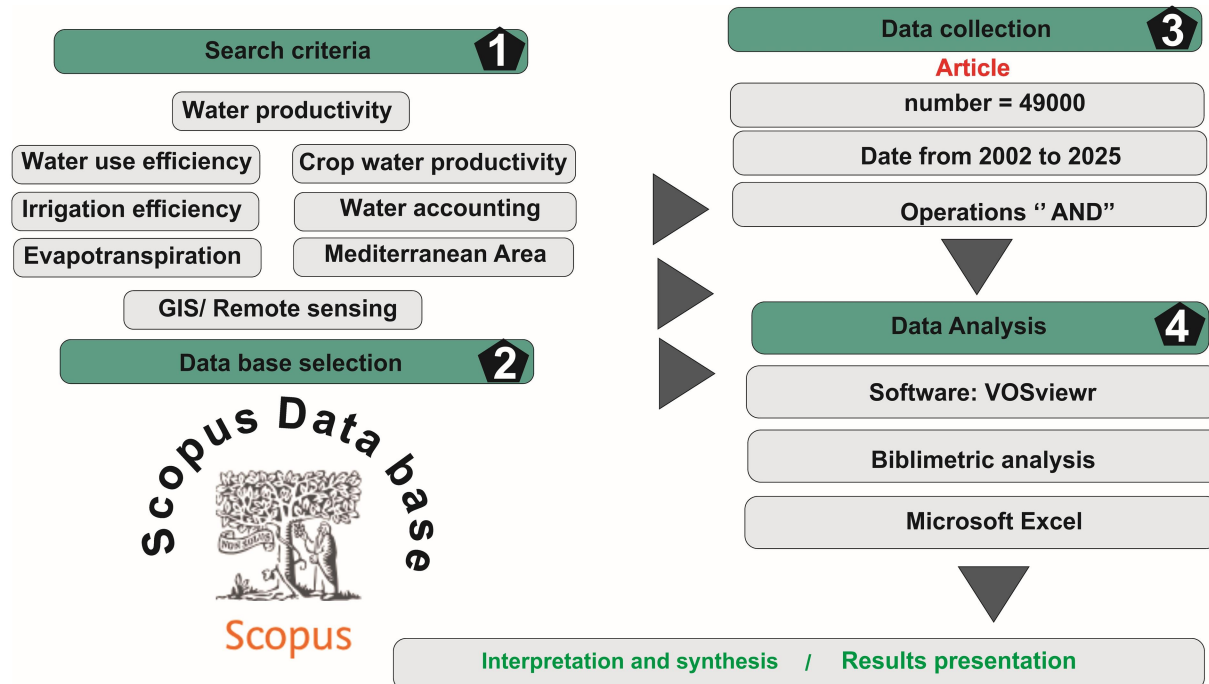


Fig. 1. Bibliometric and systematic literature review workflow.

dataset of scientific articles published between 2002 and 2025 was compiled. The selected time span reflects the rapid expansion of water productivity research following the growing global emphasis on water scarcity, climate change adaptation, and sustainable agriculture. Publications were filtered based on relevance, document type (articles and reviews), and language (English) to ensure data consistency and comparability. Classification of publications as Mediterranean was conducted using the Köppen–Geiger climate classification system. Studies were categorized as Mediterranean if they focused on areas characterized by Csa or Csb climates. This classification enabled a climate-based regional comparison of research trends and thematic priorities.

In the final phase, the results were synthesized through qualitative and quantitative interpretation. Bibliometric indicators such as annual publication trends, leading countries, influential authors, source journals, and keyword co-occurrence networks were analyzed. Network visualizations generated using VOSviewer were complemented with descriptive statistical analyses performed in Microsoft Excel. This integrative approach enabled a comprehensive interpretation of scientific development, collaboration patterns, and thematic evolution within water productivity research in Mediterranean

environments.

3. RESULTS

3.1. Distribution of Annual Scientific Production on Water Productivity

The annual distribution of scientific publications represents a key indicator for assessing the evolution, maturity, and research intensity within a specific scientific domain (Cronin, 2001; Hicks, 2004). In the context of water productivity research, analyzing the temporal distribution of publications provides valuable insights into the development of knowledge, emerging priorities, and the growing scientific response to global water scarcity and sustainable agricultural challenges. The annual publication data retrieved from the Scopus database reveal the progression of research output on water productivity in Mediterranean regions over the study period (Fig. 2).

The analysis indicates a gradual increase in the number of publications over time, reflecting the rising importance of water productivity as a critical component of sustainable water resource management and climate-resilient agriculture. This upward trend is closely associated with increasing global awareness of water scarcity, the expansion of remote sensing and modelling tools such as SWAT, and the growing emphasis on improving agricultural water use efficiency. Periods of accelerated publication growth may

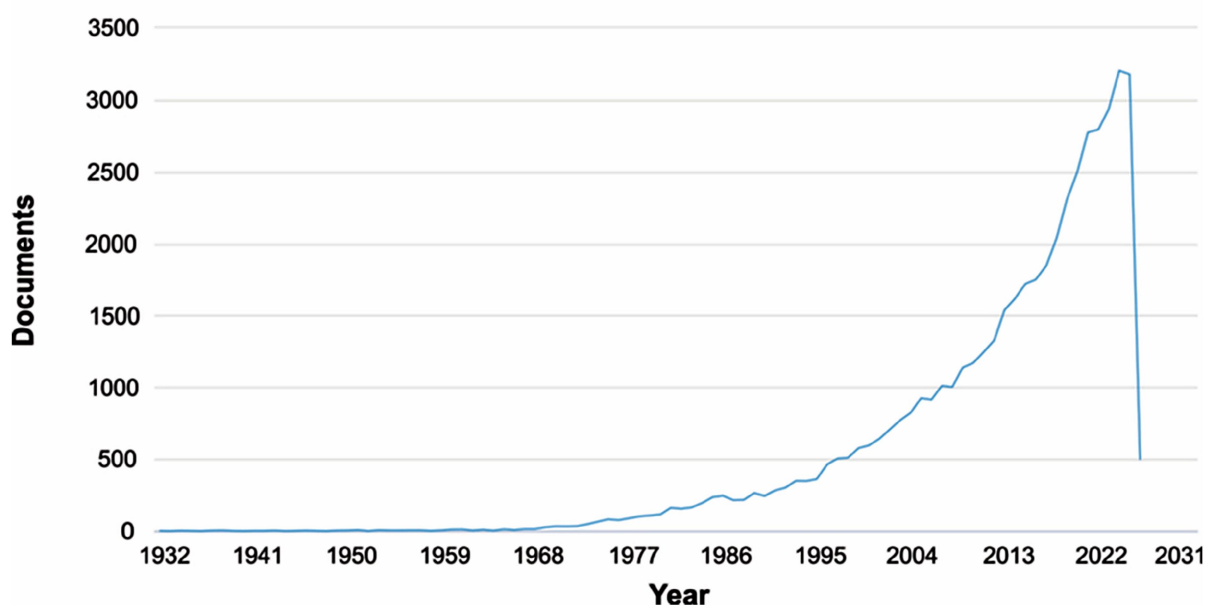


Fig. 2. Annual distribution of publications on water productivity with notable peaks in 1977 and 2025.

correspond to advances in Earth observation technologies, international water management initiatives, and increased research funding directed toward climate adaptation and food security.

Furthermore, fluctuations in annual publication output may reflect variations in regional research capacity, technological adoption, policy priorities, and environmental pressures. Mediterranean regions, characterized by high water stress and vulnerability to climate change, have attracted increasing scientific attention due to the urgent need for sustainable water management solutions. These patterns highlight the dynamic and evolving nature of water productivity research and underscore its growing relevance within the broader fields of hydrology, environmental science, and agricultural sustainability. Understanding these temporal trends provides important insights into the trajectory of scientific development and supports the identification of emerging research directions and knowledge gaps (Nowotny et al., 2001; Hall et al., 2012).

3.2. Top Productive Countries in Water Productivity Research

Fig. 3 presents the distribution of Scopus-indexed publications on water productivity according by country, highlighting the ten most productive nations in Mediterranean regions. The geographical pattern of contributions reveals a clear concentration of research activity in countries where water scarcity, climate variability, and agricultural water demand constitute major socio-environmental challenges. This distribution not only reflects

differences in scientific capacity and research investment, but also underscores the strategic importance of water productivity as a response to regional water stress.

In the Mediterranean region (Fig. 3), France, Spain and Italy stand out as the leading contributors, occupying prominent positions in terms of publication output. Their leadership can be attributed to strong academic institutions, well-developed irrigation infrastructures, and long-standing expertise in agro-hydrological research. All countries have actively investigated crop water productivity, deficit irrigation strategies, evapotranspiration modelling, and the integration of remote sensing and GIS tools to enhance sustainable agricultural water management. Egypt, Switzerland, and Portugal also demonstrate substantial research engagement, reflecting similar climatic constraints and shared regional priorities related to drought mitigation and efficient water allocation. In North Africa, Algeria, Morocco, and Tunisia contribute a growing body of literature, highlighting increasing scientific attention toward improving irrigation performance, strengthening food security, and adapting agricultural systems to intensifying water scarcity. The presence of additional contributions from countries such as France and Turkey further illustrates the collaborative and transnational dimension of water productivity research within the Mediterranean basin.

3.3. Publications by Subject Area

The distribution of publications by subject area, as indexed in the Scopus database, provides valuable insights into the disciplinary structure

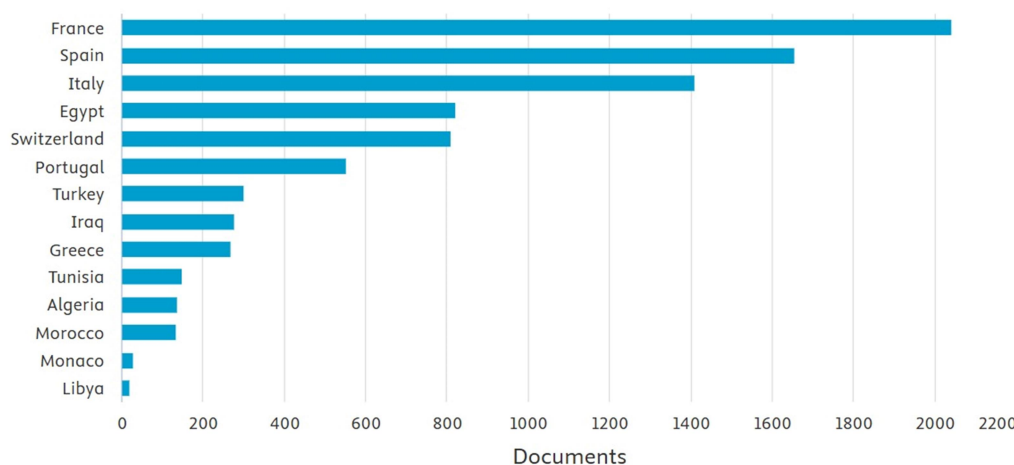


Fig. 3. Number of documents by country

and interdisciplinary character of water productivity research (Fig. 4). In the Mediterranean region, the majority of publications are concentrated in Environmental Science, which represents the dominant field of study. This prominence reflects the strong linkage between water productivity, water scarcity, ecosystem sustainability, and climate adaptation strategies. Earth and Planetary Sciences constitute the second most represented subject area, highlighting the importance of hydrological processes, climate dynamics, and land–water interactions in understanding water productivity under Mediterranean climatic conditions. Agricultural and Biological Sciences also account for a substantial share of publications, underscoring the central role of crop modelling, irrigation management, and agronomic performance in improving water use efficiency. Smaller yet meaningful contributions arise from Social Sciences, reflecting the growing

recognition of governance, policy, and socio-economic dimensions of water management, as well as from Engineering and Decision Sciences, which emphasize technological innovation, irrigation optimization, and water allocation strategies.

3.4. Most Research-Active Affiliations

The analysis of institutional affiliations reveals the universities and research organizations that have played a leading role in advancing water productivity research within Mediterranean regions (Fig. 5). The most productive institutions include prominent European research universities and specialized agricultural research centers, with several institutions contributing multiple publications. Their leadership reflects strong expertise in irrigation science, agro-hydrology, remote sensing applications, and climate adaptation research. The presence of research foundations and national agricultural institutes among the top

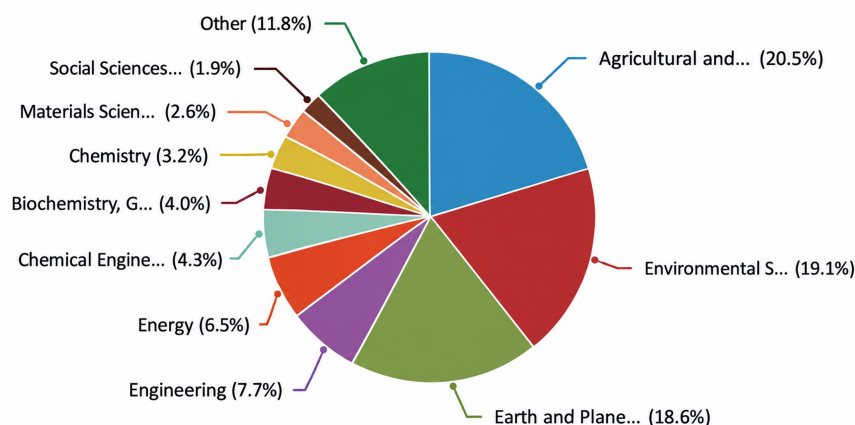


Fig. 4. Distribution of scientific publications by subject area in Mediterranean region.

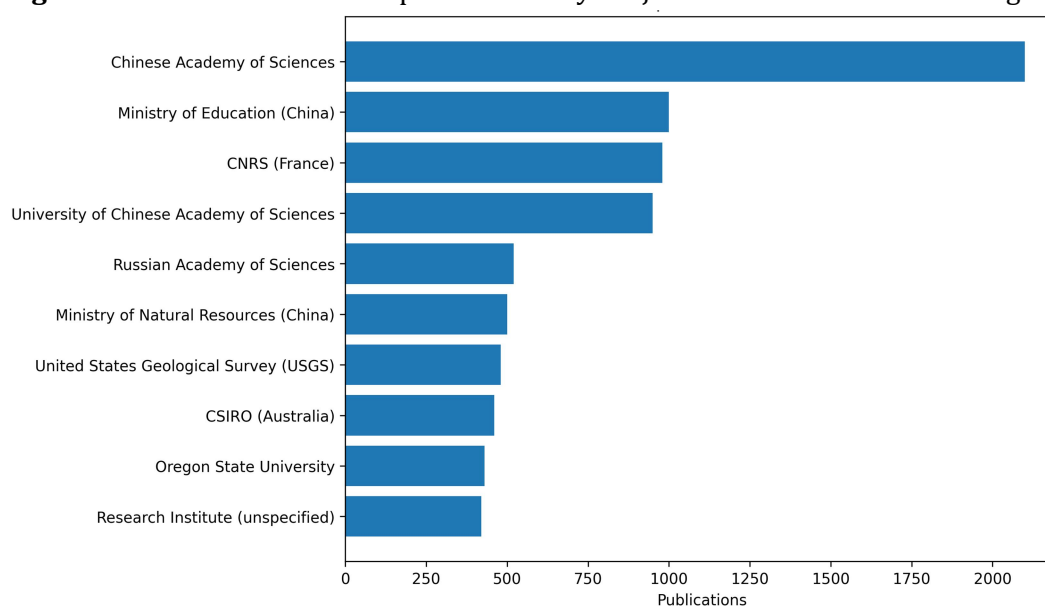


Fig. 5. Number of scientific documents related to water productivity.

contributors further illustrates the applied and policy-relevant nature of water productivity studies in Mediterranean countries. Government-supported research bodies and academies of sciences feature prominently, indicating substantial institutional investment in water and agricultural research. The distribution of affiliations also shows that, beyond the top contributors, numerous universities and research institutes participate with smaller but significant outputs, reflecting a relatively broad institutional engagement in water productivity studies.

Collectively, the affiliation analysis underscores the concentration of scientific production within well-established research institutions, while also demonstrating expanding participation from diverse academic and governmental organizations. This pattern highlights the importance of institutional capacity, funding structures, and international collaboration networks in shaping the development and dissemination of water productivity research across Mediterranean environments.

3.5. Keywords Co-Occurrence Analysis and Citation by sources

The keyword co-occurrence network derived from the Scopus dataset (February 2026 export) reveals a structurally complex and conceptually evolving research landscape marked by strong interdisciplinarity and methodological convergence. The network is organized around three dominant yet interlinked thematic domains: (i) coupled hydro-biogeochemical processes at ecosystem and basin scales, (ii) crop physiological optimization under abiotic stress conditions, and (iii) soil-water conservation embedded within sustainability-oriented management and decision-support frameworks (Fig. 6A). The prominence of terms such as water-carbon coupling, vegetation structure, non-stationary dynamics, and geographically explicit basin identifiers reflects a paradigmatic shift toward integrated environmental modeling that accounts for climate-induced variability and feedback mechanisms between hydrological and carbon cycles. The recurrence of “non-stationary dynamics” signals growing recognition that traditional stationary hydrological assumptions are increasingly inadequate in the context of accelerating climate change, thereby reinforcing the adoption of dynamic, spatially explicit modeling approaches. Concurrently, a tightly connected cluster centered on chlorophyll

fluorescence, photosynthetic rate, seed priming, polyethylene glycol, potassium nitrate, and abiotic stress tolerance underscores the mechanistic turn in water productivity research, where plant-level physiological diagnostics and biochemical enhancement strategies are deployed to mitigate drought stress and stabilize yields.

From the visualization of Fig. 6B, several journals appear as highly influential citation sources: Scientific Reports shows a high-density yellow area, indicating that it is one of the most highly cited and central sources in the dataset. Communications Earth and Environment also appears with high density, suggesting significant citation impact. Nature Communications demonstrates notable citation strength. Carbon Balance, Management, and Discover Sustainability show moderate citation density. Microbial Ecology appears with lower density compared to the leading journals. The spatial separation between journals suggests limited co-citation clustering among them, meaning that although these journals are influential, they may represent slightly different thematic focuses within the broader research domain.

Overall, the visualization highlights that the field is mainly influenced by high-impact, multidisciplinary journals focused on environmental and earth sciences.

This micro-scale experimental orientation complements macro-scale ecosystem modeling, indicating a multi-scalar integration within the field. A third thematic axis, defined by soil and water conservation, erosion control, controlled grazing, sustainability, and decision-support methodologies such as AHP, demonstrates the growing incorporation of multi-criteria evaluation tools and policy-relevant planning instruments. This reflects a transition from isolated biophysical assessments toward comprehensive socio-environmental management frameworks capable of balancing ecological resilience, agricultural productivity, and resource governance. Furthermore, the appearance of biotechnology-related terms such as corn steep water, *Bacillus licheniformis*, and fed-batch fermentation suggests an expanding nexus between water resource management and circular bioeconomy innovation, indicating that water-related research is increasingly aligned with resource recovery and sustainable production paradigms. Overall, the keyword structure reveals a field in active transformation,

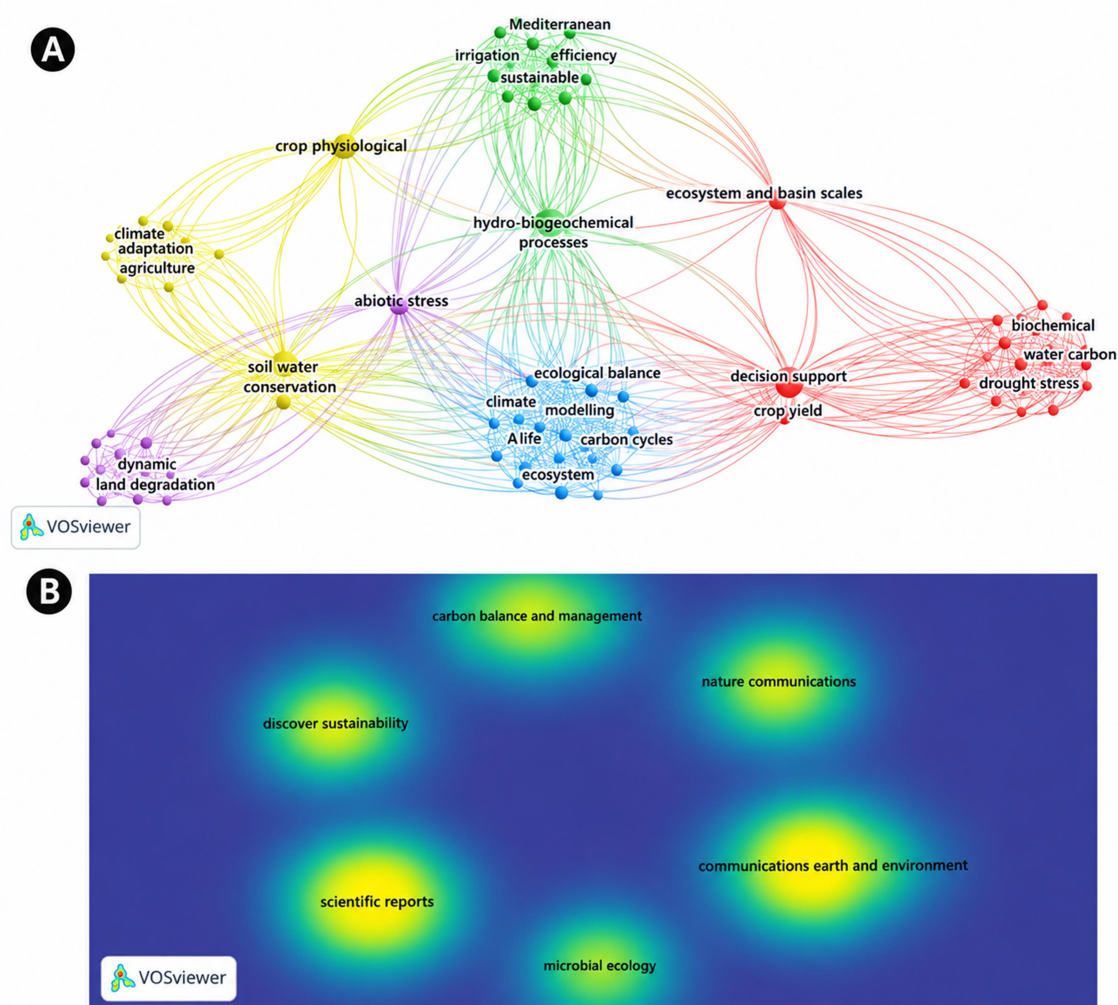


Fig. 6. Keyword co-occurrence networks related to water productivity (A). Citation by sources (B).

characterized by methodological pluralism, cross-scale integration, and convergence toward a systems-based water–energy–food–ecosystem nexus perspective. The relatively dispersed repetition of individual keywords further suggests that the domain remains in a dynamic expansion phase rather than a state of thematic saturation, reflecting ongoing conceptual diversification and emerging research frontiers.

3.6. Authorship Structure and Scientific Contribution Patterns

The authorship analysis complements the thematic findings by revealing a distributed, collaborative, and structurally emergent research community. In contrast to consolidated scientific domains dominated by a small cohort of highly prolific scholars, the present dataset exhibits broad participation, with the majority of authors contributing a single publication. This pattern indicates that the research field is currently characterized by intellectual diffusion

rather than hierarchical concentration, consistent with expanding interdisciplinary domains addressing complex sustainability challenges. The prevalence of multi-author publications underscores the inherently integrative nature of contemporary water-related research, which necessitates collaboration among hydrologists, ecologists, plant physiologists, agronomists, environmental engineers, and sustainability analysts. Such cross-disciplinary collaboration reflects the systemic complexity of water productivity and resource management issues, where ecological modeling, experimental physiology, land-use planning, and decision-support methodologies must be synthesized to generate actionable knowledge.

The absence of strong authorship concentration may also be partially attributed to the temporal recency of the dataset, as bibliometric leadership and citation centrality typically consolidate over extended time horizons. Nevertheless, the

observed collaboration structures demonstrate adaptive research networks capable of integrating diverse expertise in response to climate variability, land degradation, and agricultural sustainability pressures. Importantly, the distributed authorship profile aligns with the thematic diversification identified in the keyword analysis, suggesting that the field is simultaneously expanding conceptually and organizationally. Rather than reflecting fragmentation, this dispersion indicates methodological openness and exploratory innovation, hallmarks of domains undergoing rapid development. As the field matures, it is plausible that clearer intellectual hubs and more centralized collaboration clusters will emerge; however, the current structure highlights a vibrant and evolving scientific ecosystem grounded in interdisciplinarity, methodological integration, and responsiveness to global environmental challenges.

3.6. Top Authors on the Topic of Water Productivity

The analysis of leading authors in water productivity research reveals a moderately distributed yet regionally differentiated pattern of scientific contribution. In the Mediterranean region, authorship appears relatively dispersed, with the most productive researcher contributing two publications, while the remaining leading authors each published a single article. This distribution suggests that Mediterranean water productivity research is characterized by broad participation across multiple research groups rather than concentration within a small core of highly prolific scholars. Such dispersion likely reflects the interdisciplinary nature of water productivity studies in this region, which integrate irrigation efficiency assessment, crop water requirement modeling, evapotranspiration estimation, remote sensing applications, and agro-hydrological simulation within diverse agricultural systems. This modest concentration of productivity may be associated with sustained research programs addressing acute water scarcity, drought resilience, and irrigation optimization in water-limited environments.

Overall, the authorship patterns indicate that water productivity research remains an expanding and collaborative domain, shaped by regional environmental pressures and interdisciplinary integration rather than by dominant centralized leadership. The

combination of distributed participation in the Mediterranean regions reflects differing levels of research consolidation, yet both regions demonstrate active scientific engagement in advancing water-use efficiency and sustainable agricultural management.

4. DISCUSSION

The bibliometric analysis of water productivity research across Mediterranean regions reveals clear regional contrasts in scientific focus, methodological orientation, and research intensity, while simultaneously highlighting converging priorities driven by global water scarcity and climate variability. Semi-arid regions consistently demonstrate strong and sustained research growth, reflecting the acute vulnerability of these environments to water deficits, high evapotranspiration rates, and recurrent drought events (Ferreira & Soriano, 2007; Rockström et al., 2010; Molden et al., 2010). In such contexts, improving water productivity is directly linked to food security, agricultural resilience, and sustainable rural livelihoods (FAO, 2017; Brauman et al., 2013). Consequently, research frequently emphasizes irrigation scheduling optimization, deficit irrigation strategies, evapotranspiration modeling, and precision agriculture technologies aimed at maximizing yield per unit of water consumed (Zwart & Bastiaanssen, 2004; Pereira et al., 2012; Geerts & Raes, 2009; Salman et al., 2025; Gopal et al., 2025; Mínguez & García-Tejera, 2026).

In contrast, the Mediterranean region exhibits more variable research output over time, potentially influenced by shifting policy frameworks, funding priorities, and evolving environmental directives such as the EU Water Framework Directive and climate adaptation strategies (Garrido & Dinar, 2009; Iglesias et al., 2011; Kiptala et al., 2013; Karimi & Bastiaanssen, 2015; Busschaert et al., 2022; Bwambale et al., 2022; Raes et al., 2023; Molénat et al., 2023; Lakhari et al., 2024; Pierre et al., 2024; Salman et al., 2025; Gopal et al., 2025; Mínguez & García-Tejera, 2026). Mediterranean agriculture is characterized by heterogeneous landscapes, perennial cropping systems (e.g., olives, vineyards, citrus), and pronounced seasonal rainfall patterns, which necessitate integrated water allocation and irrigation efficiency improvements (Morison et al., 2008; Costa et al., 2007). Research in this region frequently integrates crop simulation models, soil water balance approaches, and geospatial

tools to manage water demand within complex agro-ecosystems (Raes et al., 2009; Allen et al., 1998). Countries such as Italy, Spain, and Greece remain prominent contributors to Mediterranean water productivity research, addressing challenges linked to water competition among agricultural, urban, and environmental sectors (Daccache et al., 2014; Expósito & Berbel, 2017). The annual distribution of publications suggests a steady upward trend in semi-arid research output, reflecting intensifying climate pressures and increasing global recognition of water-use efficiency as a strategic priority (Wheeler & von Braun, 2013; Tilman et al., 2011). Meanwhile, Mediterranean research shows episodic peaks, potentially associated with extreme drought events, technological advancements, or funding cycles. This divergence underscores the stronger structural urgency driving semi-arid water productivity studies. Methodologically, the frequent application of models such as FAO's AquaCrop, CROPWAT, and other crop-water productivity simulation tools highlights the central role of predictive modeling in optimizing irrigation and evaluating climate adaptation scenarios (Steduto et al., 2009; Raes et al., 2009). Remote sensing-based evapotranspiration estimation methods, including SEBAL and METRIC, are increasingly used to quantify spatial water productivity patterns and monitor irrigation performance (Bastiaanssen et al., 1998; Allen et al., 2007). Hydrological modeling and water accounting frameworks further support basin-scale assessment of water allocation efficiency (Molden et al., 2007; Karimi et al., 2013; Raes et al., 2023; Molénat et al., 2023; Lakhiar et al., 2024; Pierre et al., 2024; Gopal et al., 2025; Mínguez & García-Tejera, 2026). Despite these advancements, limitations persist, including uncertainties in climate projections, scale mismatches between field and basin analyses, and insufficient integration of socio-economic variables into productivity assessments (Perry et al., 2009; Ward & Pulido-Velazquez, 2008).

Bibliometric tools such as VOSviewer have proven instrumental in identifying thematic clusters and intellectual linkages within the water productivity domain. Co-occurrence network analysis highlights dominant keywords including "irrigation efficiency," "evapotranspiration," "deficit irrigation," "remote sensing," "GIS," and "climate change," underscoring the integration of technological and modeling approaches (van Eck & Waltman,

2010). Mediterranean studies tend to emphasize irrigation management within perennial cropping systems and landscape-level optimization, whereas semi-arid research prioritizes drought adaptation, water scarcity mitigation, and resilience-building strategies (Rockström et al., 2007; Fereres et al., 2011). Leading contributors in both regions demonstrate moderate productivity, reflecting a distributed authorship structure rather than centralized academic dominance, which is characteristic of rapidly evolving interdisciplinary fields (Cronin, 2001; Hicks et al., 2015).

To advance water productivity research, future investigations must adopt integrative water-energy-food nexus frameworks that move beyond yield-per-water metrics and incorporate ecological sustainability, economic viability, and institutional governance dimensions (Hoff, 2011; Biggs et al., 2015). Greater emphasis should be placed on region-specific adaptation strategies, including regulated deficit irrigation, drought-tolerant crop varieties, soil moisture conservation techniques, and smart irrigation systems driven by real-time sensor networks and artificial intelligence (Jones, 2004; Liakos et al., 2018). High-resolution satellite imagery, UAV-based monitoring, and machine learning-driven evapotranspiration modeling can significantly enhance spatial and temporal precision in water productivity assessments (Zhang et al., 2019; Maes & Steppe, 2012). Addressing existing gaps such as limited socio-economic integration, insufficient long-term field validation, and underrepresentation of smallholder systems will improve the policy relevance of water productivity research, particularly in water-stressed regions facing rapid demographic growth (Pretty et al., 2011; Wheeler & von Braun, 2013). Stronger transdisciplinary collaboration linking scientific innovation with farmer practices, irrigation agencies, and policymakers will be essential to translate productivity gains into sustainable outcomes. From a policy perspective, bibliometric insights can guide strategic investment in irrigation modernization, digital agriculture, and climate adaptation initiatives under frameworks such as the Sustainable Development Goals (SDGs) and integrated water resource management (IWRM) strategies (UN, 2015; GWP, 2000). Enhancing international collaboration and capacity-building efforts in underrepresented yet highly vulnerable regions will further strengthen global water resilience.

Ultimately, the continued integration of technological innovation, environmental sustainability, and socio-economic considerations will be critical to ensuring that water productivity improvements contribute not only to higher yields but also to long-term ecosystem stability and food system resilience.

5. CONCLUSION

This bibliometric review provides a comprehensive assessment of scientific research on water productivity in Mediterranean regions, offering valuable insights into thematic evolution, geographical contributions, and methodological trends. The application of bibliometric tools such as VOSviewer has enabled the identification of dominant research clusters, collaboration structures, and emerging interdisciplinary linkages, clarifying the intellectual structure of the field. The widespread adoption of crop simulation models, evapotranspiration estimation techniques, and remote sensing technologies underscores the central role of innovation in advancing water productivity assessment and irrigation management. However, significant gaps remain, particularly regarding the integration of socio-economic factors, institutional governance, and long-term adaptation dynamics. Addressing these limitations requires more holistic and systems-oriented approaches that bridge agronomy, hydrology, climate science, economics, and policy analysis. Future research should expand its geographical scope to include tropical, temperate, and highly vulnerable developing regions, thereby fostering a more globally inclusive understanding of water productivity dynamics. Incorporating multiple bibliographic databases and leveraging emerging analytical techniques such as machine learning and big-data analytics will enhance methodological robustness. Moreover, longitudinal studies evaluating the real-world impacts of water productivity innovations on agricultural sustainability and policy implementation are needed to strengthen the evidence base. In conclusion, advancing water productivity research through interdisciplinary integration, technological innovation, and policy alignment will be essential for ensuring sustainable agricultural development under increasing climate and water resource pressures. Such efforts will play a pivotal role in strengthening global food security, enhancing ecosystem resilience, and promoting sustainable water management worldwide.

REFERENCES

- Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, FAO, Rome, Italy.
- Allen, R. G., Tasumi, M., & Trezza, R. (2007). Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) Model. *Journal of Irrigation and Drainage Engineering*, 133, 380–394.
- Anderson, M. C., Norman, J. M., Mecikalski, J. R., Otkin, J. A., & Kustas, W. P. (2012). A thermal-based remote sensing technique for routine mapping of land-surface evapotranspiration. *Water Resources Research*, 48, W04520.
- Aria, M., & Cuccurullo, C. (2017). bibliometrix: An R-tool for comprehensive science mapping analysis. *Journal of Informetrics*, 11, 959–975.
- Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment. Part I: Model development. *Journal of the American Water Resources Association*, 34, 73–89.
- Bastiaanssen, W. G. M., Menenti, M., Feddes, R. A., & Holtslag, A. A. M. (1998). A remote sensing surface energy balance algorithm for land (SEBAL): 1. Formulation. *Journal of Hydrology*, 212–213, 198–212. [https://doi.org/10.1016/S0022-1694\(98\)00253-4](https://doi.org/10.1016/S0022-1694(98)00253-4)
- Bastiaanssen, W. G. M., Noordman, E. J. M., Pelgrum, H., Davids, G., Thoreson, B. P., & Allen, R. G. (2005). SEBAL model with remotely sensed data to improve water-resources management under actual field conditions. *Journal of Irrigation and Drainage Engineering*, 131(1), 85–93. [https://doi.org/10.1061/\(ASCE\)0733-9437\(2005\)131:1\(85\)](https://doi.org/10.1061/(ASCE)0733-9437(2005)131:1(85))
- Biggs, E. M., Bruce, E., Boruff, B., Duncan, J. M. A., Horsley, J., Pauli, N., McNeill, K., & Li, F. (2015). Sustainable development and the water-energy-food nexus: A perspective on livelihoods. *Environmental Science and Policy*, 54, 389–397.
- Busschaert, L., de Roos, S., Thiery, W., Raes, D., & De Lannoy, G. J. (2022). Net irrigation requirement under different climate scenarios using AquaCrop over Europe. *Hydrology and Earth System Sciences*, 26(14), 3731–3752.
- Costa, J. M., Ortuño, M. F., Chaves, M. M., Escalona, J. M., Medrano, H., & Bota, J. (2007). Deficit irrigation as a strategy to save water:

- Physiological implications. *Agricultural Water Management*, 92, 4–17.
- Cronin, B. (2001). The citation process: The role and significance of citations in scientific communication. Taylor Graham, London, UK.
- Daccache, A., Ciurana, J., Camacho, E., Rodriguez-Diaz, J. A., & Knox, J. W. (2014). Vulnerability of Mediterranean irrigation to climate change. *Agricultural Water Management*, 135, 51–62.
- Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research*, 133, 285–296.
- Ellegaard, O., & Wallin, J. A. (2015). The bibliometric analysis of scholarly production: How great is the impact? *Scientometrics*, 105, 1809–1831.
- Elsevier. (2018). Scopus content coverage guide. Elsevier, Amsterdam, The Netherlands.
- Expósito, A., & Berbel, J. (2017). Water productivity in European agriculture: Lessons from Mediterranean case studies. *Water*, 9, 283.
- FAO. (2017). The state of food and agriculture. Food and Agriculture Organization of the United Nations, Rome, Italy.
- FAO. (2020). Water productivity: Guidelines for sustainable use. Food and Agriculture Organization of the United Nations, Rome, Italy.
- Falagas, M. E., Pitsouni, E. I., Malietzis, G. A., & Pappas, G. (2008). Comparison of PubMed, Scopus, Web of Science, and Google Scholar: Strengths and weaknesses. *FASEB Journal*, 22, 338–342.
- Falkenmark, M., & Rockström, J. (2006). Balancing water for humans and nature: The new approach in ecohydrology. Earthscan, London, UK.
- Fereres, E., & Soriano, M. A. (2007). Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany*, 58, 147–159.
- Fereres, E., Soriano, M. A., Pala, M., & Lloveras, J. (2011). Improving water productivity of irrigated crops in Mediterranean environments. *Agricultural Water Management*, 98, 1225–1231.
- Fereres, E., Soriano, M. A., & Playán, E. (2011). Deficit irrigation in Mediterranean agriculture: Research advances. *Irrigation Science*, 29, 97–110.
- Garrido, A., & Dinar, A. (2009). Water allocation mechanisms: Principles and experiences. *Water Policy*, 11, 47–65.
- Gassman, P. W., Reyes, M. R., Green, C. H., & Arnold, J. G. (2007). The soil and water assessment tool: Historical development, applications, and future research directions. *Transactions of the ASABE*, 50, 1211–1250.
- Geerts, S., & Raes, D. (2009). Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agricultural Water Management*, 96, 1275–1284.
- Gopal, R., Singh, N. K., Ashoka, P., Yadav, V., Mohanty, L. K., Panotra, N., Shashidhar, K. S., Kumar, J., Anand, P., & Pathania, D. (2025). Precision irrigation techniques for optimizing water use efficiency in agriculture. *Archives of Current Research International*, 25(12), 347–362.
<https://doi.org/10.9734/acri/2025/v25i121675>
- GWP. (2000). Integrated water resources management. Global Water Partnership, Stockholm, Sweden.
- Hall, C., Hughes, A., & Martin, B. (2012). Science mapping and bibliometric analysis: A practical guide. *Research Evaluation*, 21, 251–263.
- Hicks, D. (2004). The four literatures of social science. In: *Handbook of Quantitative Science and Technology Research*, pp. 473–496. Springer, Dordrecht, The Netherlands.
- Hoff, H. (2011). Understanding the nexus. Background paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus. Stockholm Environment Institute, Stockholm, Sweden.
- Iglesias, A., & Garrote, L. (2015). Adaptation strategies for agricultural water management under climate change in Mediterranean regions. *Climatic Change*, 132, 135–149.
- Iglesias, A., Garrote, L., Flores, F., & Moneo, M. (2011). Challenges to manage the risk of water scarcity in agriculture under climate change in Mediterranean regions. *Mitigation and Adaptation Strategies for Global Change*, 16, 383–395.
- Jones, H. G. (2004). Use of thermography for crop water stress assessment. *Journal of Experimental Botany*, 55, 227–236.
- Karimi, P., & Bastiaanssen, W. G. (2015). Spatial evapotranspiration, rainfall and land use data in water accounting—Part 1: Review of the accuracy of the remote sensing data. *Hydrology and Earth System Sciences*, 19(1), 507–532.
- Karimi, P., Bastiaanssen, W. G. M., & Molden, D. J. (2013). Application of remote sensing in basin-scale water productivity assessment. *Agricultural Water Management*, 130, 1–13.
- Kipper, K., Lehmann, E., & Schultz, M. (2020). Bibliometric tools and software for network

- analysis in science. *Scientometrics*, 124, 1239–1262.
- Kiptala, J. K., Mohamed, Y., Mul, M. L., & Van der Zaag, P. (2013). Mapping evapotranspiration trends using MODIS and SEBAL model in a data scarce and heterogeneous landscape in Eastern Africa. *Water Resources Research*, 49(12), 8495–8510.
- Kulkarni, A. V., Aziz, B., Shams, I., & Busse, J. W. (2009). Comparison of citation databases: Scopus, Web of Science, and Google Scholar. *Journal of the Medical Library Association*, 97, 236–241.
- Liakos, K. G., Busato, P., Moshou, D., Pearson, S., & Bochtis, D. (2018). Machine learning in agriculture: A review. *Sensors*, 18, 2674.
- Maes, W., & Steppe, K. (2012). Estimating evapotranspiration and drought stress with ground-based thermal remote sensing. *Hydrology and Earth System Sciences*, 16, 133–149.
- Mínguez, M. I., & García-Tejera, O. (2026). Cropping systems in Spain: A paradigm of Mediterranean agriculture. In: *Crop Physiology*, pp. 35–53. Academic Press.
- Molden, D. J. (2007). Water for food, water for life: A comprehensive assessment of water management in agriculture. Earthscan/International Water Management Institute, London, UK.
- Molden, D. J., Oweis, T., Steduto, P., Kijne, J. W., & Hanjra, M. A. (2010). Pathways for increasing agricultural water productivity. *Agricultural Water Management*, 97, 520–530.
- Molénat, J., Barkaoui, K., Benyoussef, S., Mekki, I., Zitouna, R., & Jacob, F. (2023). Diversification from field to landscape to adapt Mediterranean rainfed agriculture to water scarcity in climate change context. *Current Opinion in Environmental Sustainability*, 65, 101336.
- Montalván-Burbano, N., Dávila, M., & Poveda, M. (2020). Using VOSviewer for bibliometric network analysis: Applications in environmental research. *Environmental Science and Pollution Research*, 27, 12345–12357.
- Morison, J. I. L., Baker, N. R., Mullineaux, P. M., & Davies, W. J. (2008). Improving water use in crop production. *Philosophical Transactions of the Royal Society B*, 363, 639–658.
- Nowotny, H., Scott, P., & Gibbons, M. (2001). Rethinking science: Knowledge and the public in an age of uncertainty. Polity Press, Cambridge, UK.
- OECD. (2021). Water governance in OECD countries: A multi-level approach. Organisation for Economic Co-operation and Development, Paris, France.
- Pereira, L. S., Cordery, I., & Iacovides, I. (2012). Improved indicators of water use performance and productivity for sustainable water conservation and saving. *Agricultural Water Management*, 108, 39–51. <https://doi.org/10.1016/j.agwat.2011.08.022>
- Perry, C., Steduto, P., Allen, R. G., & Burt, C. M. (2009). Increasing productivity in irrigated agriculture: Agronomic constraints and hydrological realities. *Agricultural Water Management*, 96, 1517–1524.
- Playán, E., & Mateos, L. (2006). Modern developments in irrigation management: Efficiency and sustainability. *Agricultural Water Management*, 86, 1–21.
- Pranckutė, R., Ragauskaitė, A., & Tamulevičius, A. (2021). Scopus database coverage and bibliometric analysis: Applications and limitations. *Scientometrics*, 126, 3553–3573.
- Pretty, J., Toulmin, C., & Williams, S. (2011). Sustainable intensification in African agriculture. *International Journal of Agricultural Sustainability*, 9, 5–24.
- Raes, D., Fereres, E., García Vila, M., Curnel, Y., Knoden, D., Çelik, S. K., Ucar, Y., Türk, M., & Wellens, J. (2023). Simulation of alfalfa yield with AquaCrop. *Agricultural Water Management*, 284, 108341. <https://doi.org/10.1016/j.agwat.2023.108341>
- Raes, D., Steduto, P., Hsiao, T. C., & Fereres, E. (2009). AquaCrop—The FAO crop model to simulate yield response to water: II. Main algorithms and software description. *Agronomy Journal*, 101(3), 438–447. <https://doi.org/10.2134/agronj2008.0140s>
- Raes, D., Steduto, P., Hsiao, T. C., & Fereres, E. (2018). AquaCrop version 6.0 reference manual. Food and Agriculture Organization of the United Nations, Rome, Italy.
- Rockström, J., Falkenmark, M., Karlberg, L., Hoff, H., Rost, S., & Gerten, D. (2010). Future water availability for global food production: The role of green water. *Water Resources Research*, 46, W06503.
- Rockström, J., Falkenmark, M., Lannerstad, M., Karlberg, L., Hoff, H., Rost, S., & Gerten, D. (2007). Future water availability for global food production: The potential of green water for increasing resilience to global change. *Water Resources Research*, 43, W05303.
- Rouault, P., Courault, D., Flamain, F., & Debolini, M. (2024). Unravelling the heterogeneity of farms irrigation practices on Mediterranean perennial agricultural systems for the

- optimization of water resource management. Research Square. <https://doi.org/10.21203/rs.3.rs-4580425/v1>
- Salman, M., García Vila, M., Fereres, E., Raes, D., Steduto, P., Heng, L., De Lannoy, G., Wellens, J., Foster, T., Busschaert, L., Bechtold, M., & de Roos, S. (2025). AquaCrop on the ground: Model applications for sustainable agricultural water management. FAO Water Reports No. 48, Food and Agriculture Organization of the United Nations, Rome, Italy. <https://doi.org/10.4060/cd4207en>
- Schotten, M., Schubert, A., & Glänzel, W. (2017). Bibliometrics and research evaluation in practice: Scopus and Web of Science. *Scientometrics*, 113, 1117–1129.
- Schyns, J. F., Booi, M. J., & Hoekstra, A. Y. (2019). The water footprint of wheat and maize in different climatic zones: A global assessment. *Ecological Indicators*, 99, 159–172.
- Senay, G. B., Bohms, S., Singh, R. K., Gowda, P. H., Velpuri, N. M., Alemu, H., & Verdin, J. P. (2013). Operational evapotranspiration mapping using remote sensing and weather datasets: A new parameterization for the SSEB approach. *Journal of the American Water Resources Association*, 49(3), 577–591. <https://doi.org/10.1111/jawr.12057>
- Singh, V. K., Kumari, A., & Kumar, S. (2021). Bibliometric mapping of water productivity studies: Scopus-based insights. *Environmental Monitoring and Assessment*, 193, 745.
- Steduto, P., Hsiao, T. C., Raes, D., & Fereres, E. (2009). AquaCrop—The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. *Agronomy Journal*, 101(3), 426–437. <https://doi.org/10.2134/agronj2008.0139s>
- UN. (2015). Transforming our world: The 2030 Agenda for Sustainable Development. United Nations, New York, NY, USA.
- UN-Water. (2021). Sustainable Development Goal 6 synthesis report on water and sanitation. United Nations, New York, NY, USA.
- Van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, 84, 523–538.
- Van Eck, N. J., & Waltman, L. (2010). Visualizing bibliometric networks. In: *Measuring Scholarly Impact*, pp. 285–320. Springer, Cham, Switzerland.
- Ward, F. A., & Pulido-Velazquez, M. (2008). Water conservation in irrigation can increase water use. *Proceedings of the National Academy of Sciences of the United States of America*, 105, 18215–18220.
- WWAP. (2023). The United Nations World Water Development Report 2023: Water for Climate Resilience. UNESCO, Paris, France.
- Zhang, C., Wei, Y., Li, X., & Zhao, H. (2019). Monitoring crop water productivity using satellite imagery and machine learning. *Remote Sensing*, 11, 285.
- Zhang, H., Wang, R., Li, X., & Wang, S. (2021). Mapping the intellectual structure of water productivity research: A bibliometric review. *Sustainability*, 13, 12345.
- Zwart, S. J., & Bastiaanssen, W. G. M. (2004). Review of measured crop water productivity values for irrigated wheat, rice, cotton, and maize. *Agricultural Water Management*, 69, 115–133.