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Exploring the key drivers of crop yields in Morocco – a systematic review

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Introduction: Morocco's agricultural sector faces significant socio-environmental challenges that threaten food security and economic development. A comprehensive assessment of these challenges is crucial for informed decision-making at both national and farm scales. This study aims to identify and analyze key drivers influencing crop yields in Morocco, with a focus on grain crops, by integrating climatic, socio-economic, and biophysical factors.

Methods: A systematic review of 135 peer-reviewed and grey literature sources published between 1990 and 2024 was conducted. The review examines both climatic and non-climatic factors affecting crop yields, particularly for wheat, a staple in Morocco's food system.

Results: Precipitation emerged as the primary driver of crop yields, with approximately 15.6% of the literature analyzed emphasizing its impact. Other significant factors include irrigation, fertilization, water stress, temperature, technical efficiency, soil properties, conservation agriculture, insects and pests, sowing date, drought, crop varieties and genetics, diseases, herbicides, and extreme climatic events. These drivers interact in complex ways, with precipitation and irrigation playing pivotal roles in mitigating water stress and enhancing crop productivity.

Discussion: The findings highlight the intricate dependencies between climatic and agronomic factors affecting Morocco's grain production. Understanding these interactions is essential for policymakers and farmers to develop strategies that enhance agricultural sustainability and resilience. This study provides a foundation for impact-based analysis and evidence-based decision-making to improve productivity and ensure food security in Morocco.

KEYWORDS
agriculture, crop yields, food security, climate change, Morocco

1 Introduction

Agriculture is a crucial sector for the socio-economic development of most African countries. In sub-Saharan Africa, it provides about 60% of employment and 30% of Gross Domestic Product (GDP) (World Bank, 2020; World Bank, 2021). Farming in these regions is primarily dominated by smallholder farmers, who face challenges such as limited access to technology and funding, posing significant obstacles to achieving Sustainable Development Goals 1 and 2, which aim to eradicate poverty and hunger, respectively (FAO, 2020).

In Morocco, agriculture remains a cornerstone of the economy, contributing approximately 12.04% to the national GDP and 40% to employment (Harbouze et al., 2019; World Bank, 2023). Moroccan agriculture is characterized by its diversity, encompassing traditional subsistence-based practices and commercial agriculture. Subsistence farming, which is predominantly rain-fed, constitutes most of the agricultural activity and highlights the economy's sensitivity to climatic variability (Sraïri, 2017; Lahlou et al., 2016). Conversely, commercial agriculture is concentrated in irrigated regions, accounting for only 15% of agricultural acreage yet generating 45% of agricultural GDP and 75% of agricultural exports (Lahlou et al., 2016).

Biophysical factors, such as soil quality, climate conditions and water availability, profoundly influence agricultural productivity. For instance, Morocco's vulnerability to climate extremes underscores the significance of biophysical factors in shaping agricultural outcomes (Douguedroit et al., 1998; Aux et al., 2002; Lionboui et al., 2020). On the other hand, socio-economic factors encompass elements like access to technology, funding, knowledge and government policies. In Morocco, the disparity between smallholder farmers' access to mechanization and modern inputs compared to commercial agriculture highlights the role of socio-economic factors in agricultural development (Doukkali, 2006; Bishaw et al., 2019).

Cereal production plays a vital role in Morocco's agricultural landscape and food security (FAO, 2021). According to the FAO (2020), approximately half of Morocco's farmland is dedicated to cereals, including wheat, barley, and maize, covering about 4.6 million hectares across various agroecological zones. Wheat, a staple crop, holds particular importance for livelihoods and the national economy. In the 1980s, the government launched intensification programs promoting high-yield wheat varieties, leading to an increase in wheat cultivation to around 2 million hectares during 2010–2018 (Yigezu et al., 2021a; Yigezu and El-Shater, 2021). Wheat production generated approximately USD 850 million, making it the second most valuable crop after olives (Bishaw et al., 2019).

Other important crops in Morocco include olives, citrus fruits, and vegetables. Olives are the most valuable crop, contributing significantly to agricultural exports and rural incomes (Harbouze et al., 2019). Citrus fruits, primarily oranges and mandarins, are critical export commodities, with Morocco ranking among the top global exporters (IFAD, 2021). Vegetables, including tomatoes and potatoes, are key for both domestic consumption and export markets. Additionally, legumes and fodder crops support livestock systems, which are integral to rural livelihoods.

Morocco's agricultural policies, such as the Green Morocco Plan (GMP) and the Green Generation (GG) Strategy, play a critical role in addressing the sector's challenges and enhancing its productivity. The GMP, launched in 2008, aimed to modernize agriculture by increasing output and promoting sustainable practices. It focused on integrating smallholder farmers into value chains, improving irrigation strategies, optimizing sowing timing, and adopting advanced plant protection and fertilization management techniques (Ministry of Agriculture, 2016; Balaghi et al., 2013; Gharous and Boulal, 2016; Bouras et al., 2019; Lionboui et al., 2019). By promoting mechanization and the use of modern inputs, the GMP contributed to increased yields, especially in irrigated areas. Building on the GMP's foundation, the GG strategy, introduced in 2020, emphasizes youth involvement, the adoption of sustainable technologies, and resilience to climate change (Ministry of Agriculture, 2021). Additionally, the government's efforts to align with the Sustainable Development Goals have spurred initiatives to improve farmers' access to funding, knowledge, and infrastructure (IFAD, 2021). Despite these initiatives, challenges such as soil degradation, water scarcity, and unequal access to resources persist, underscoring the need for continued policy innovation and stakeholder collaboration.

This systematic review aims to provide a comprehensive analysis of the key drivers, constraints, and policy initiatives influencing agricultural productivity in Morocco. By synthesizing existing research, the study bridges critical knowledge gaps, as previous studies often focus on specific crops or regions, limiting their applicability on a national scale. This integrated perspective offers actionable insights for improving agricultural practices and policies to address the dual goals of productivity and sustainability. The review is particularly timely, given Morocco's heightened vulnerability to climate extremes and the ongoing implementation of policy initiatives like the Green Generation Strategy. These factors underscore the pressing need for evidence-based strategies to enhance agricultural resilience and ensure sustainable crop production, contributing to broader efforts to strengthen food security and support effective policy-making.

2 Data and methods

This systematic review follows a protocol proposed by Pullin and Stewart (2006). The protocol is repeatable, dependable and objective in its evaluation of the state of current knowledge on a certain topic. It is based on six steps: establishing the specific research question; choosing the database; defining the time interval; establishing the keywords to be used in the search phase; selection of the relevant publications and extraction and analysis of the data.

2.1 Literature search and screening criteria

The research question refers to the drivers of crop yields in Morocco. Three leading databases: Scopus, Web of Science and Google Scholar were searched for relevant documents with the use of search terms using conventional bracket operators, Boolean operators and wildcards. In this case, the title, abstract, and keywords were scanned.

Keywords were used to craft a search expression that would provide results for the majority of relevant articles. The words and their synonyms were looked up in each database to factor all the important terms in the search. The search terms included the following: "crop yields in Morocco", "drivers of crop yield in Morocco", "crop yield loss in Morocco", "crop yields weather impacts in Morocco", "crop yields non-climatic variables impact in Morocco", "crop yields socio-economic impacts in Morocco". The search included the names of a variety of drivers and types of crops in our search terms: ('climate change', 'fertilizers', 'irrigation', 'soil', 'diseases', 'pests', 'crop models', 'conservation agriculture', 'genetics', 'cereal', 'legume') to refine the quality and quantity of the search. An exclusion and inclusion criteria (Table 1) were employed to limit the analysis to crop production drivers and limitations in Morocco.

2.2 Data extraction and coding

The search produced 17 798 articles in which about 500 duplicates were found and removed through manually spotting. The remaining 1208 articles were screened for the search terms and keywords in the title, abstract, and keywords sections, eliminating 400 articles. Thereafter, 486 papers were eliminated for failing to meet the eligibility criteria based on abstracts, leaving only 322 to be read in full text. Finally, 135 documents were reviewed for their relevance to the topic of study (Figure 1).

2.3 Data assessment

The following information was stored in a database for every article: First author, their affiliation, journal name, publication year, type of crops studied, crop yield factors detected in each research, study period and the main key results of each research (Supplementary Table S1).

3 Results

3.1 Trends, source and affiliations of lead authors

A total of 135 articles were eligible for review based on the predefined criteria (Figure 1). Notably, the analysis of distribution revealed that approximately (40)30% and (95)70% of the articles were grey and peer-reviewed literature, respectively (Figure 2).

Figure 3 presents the patterns of research publications on the impact of crop yields in Morocco since 1994. Overall, an upward trend in publication rates is observed since 2001. The trajectory can be delineated into distinct periods: an initial phase (1994 - 2000) with 11 (8%) publications. This phase laid the foundation for subsequent research endeavors. There was a noticeable uptick in research output between 2001 and 2008, with a total of 19(14%) publications. This period marked a significant increase in scholarly contributions, signaling the growing recognition of the importance of the research topic. The notable increase in publications between 2009 and 2024, 105 (78%), corresponds with the implementation of GMP initiative that started in 2008. The initiative led to substantial investments in agriculture aimed at modernization, increased productivity and sustainable development. Studies show that the GMP spurred research efforts on climate impact, sustainable practices and efficient irrigation systems, reflecting the alignment of national priorities with research activities (Sokol et al., 2019; Amiri et al., 2021). This alignment provides strong evidence that the observed increase in publications is directly linked to these strategic initiatives. Notably, the highest publication count was in 2021, with 18 (13%) of the selected articles, indicating a possible response to escalating demands for research and development endeavors in the field.

A range of publishers and journals played a significant role in disseminating research findings on the subject topic. In addition to the leading academic publishers, other notable contributors to the research output were National Institute of Agricultural Research (INRA) (10), and International Center for Agricultural Research in the Dry Areas (ICARDA) (5). Moreover, 38 publications were distributed among various niche journals, which cater to specific subtopics.

TABLE 1 Inclusion and exclusion criteria.

Criteria	Included	Excluded	Justification for criteria application
Date of publication	1990-2024	Before 1990	To obtain contemporary knowledge of factors affecting crop yield.
Language	English and French	All other languages	To increase readability and access to more studies
Country of study	Morocco	Beyond Morocco	To keep the scope of the systematic review intact
Article availability	Availability of full article	Full article not accessible	Due to accessibility issues
Type of article	Peer reviewed research journal articles, conference papers, book chapters, review papers, grey literature	Media reports	To improve the reliability of research results
Publication topic	Articles specifically on drivers of crop yields	Beyond the drivers of crop yields studies	To keep the scope of the systematic review focused

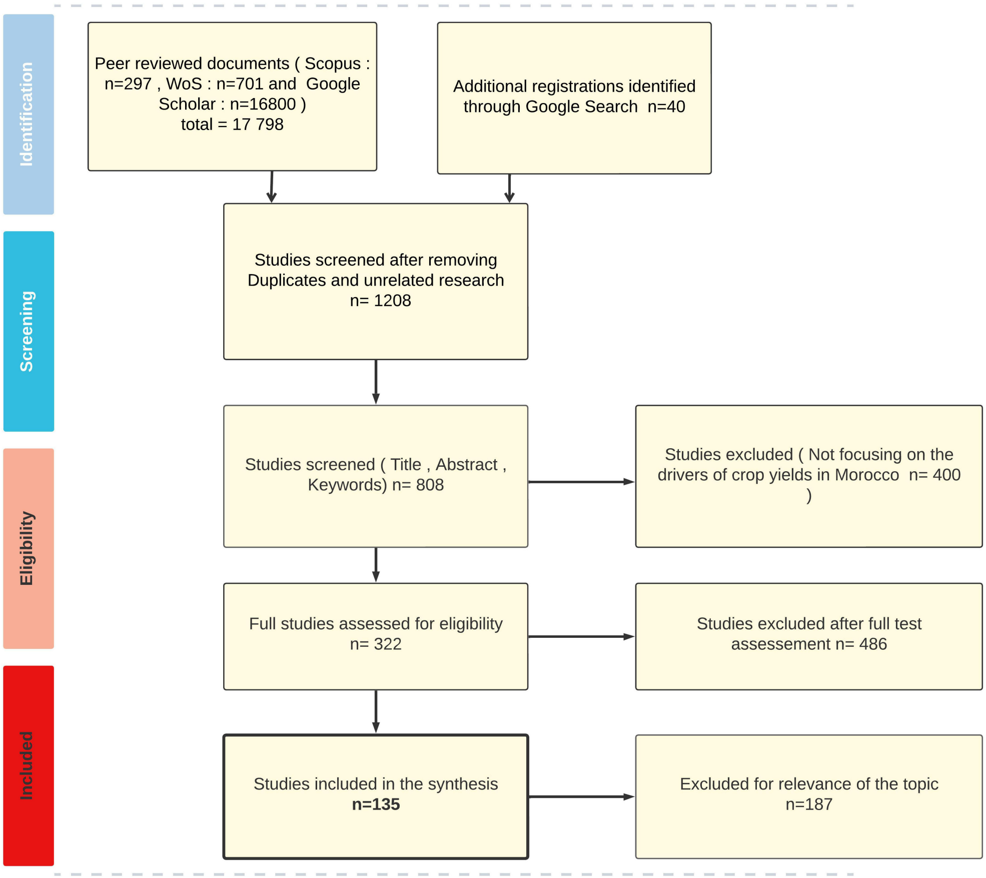

FIGURE 1
Flow chart of the systematic review process.

The distribution of lead authors across the globe (Figure 4) provides valuable insights into the research landscape. A high representation of Moroccan lead authors (62%) shows the important role of local researchers and institutions in the topic of study. Furthermore, the presence of publications with multiple country affiliations confirms the international collaboration and the recognition of the global nature of agricultural research in effort to attain food security. France emerges as a prominent contributor in 10% of the publications, indicating a close research partnership between the two countries. The contributions from Syria (4%), the United States (4%), Egypt (4%) and Italy (3%), indicate the engagement of diverse perspectives and expertise in understanding agricultural yield dynamics.

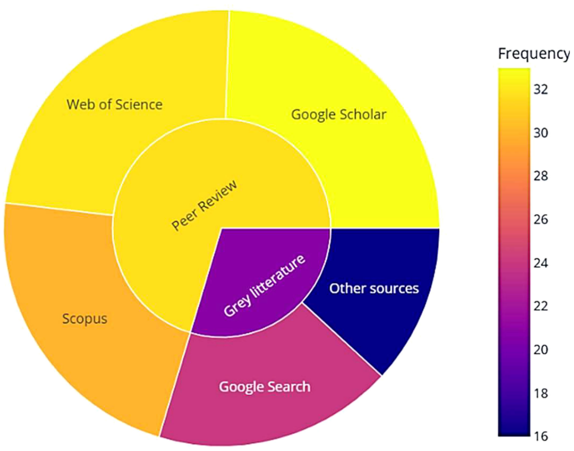

FIGURE 2
Distributions of peer-review and grey literature crop yield drivers' studies in Morocco.

An analysis of Moroccan publications based on contributing institutions provides valuable insights into the research landscape (Figure 5). The INRA contributes (29)35% of the publications, underscoring the prominent role of INRA in driving agricultural research within Morocco. Other notable contributors include the Mohamed VI Polytechnic University (UM6P), Cadi Ayyad University, and the National School of Agriculture of Meknes, each with (8)10% of the publications. Their active involvement highlights their commitment to advancing agricultural research in the country. The ICARDA Morocco and the Hassan II Institute of Agronomic and Veterinary Medicine also made substantial contributions, with (6)7% of the publications each. Furthermore, Moulay Ismail University and Sidi Mohamed Ben Abdellah University each contributed three publications, showcasing their involvement in agricultural research. Other universities, including Ibn Tofail University, Mohamed V Faculty, Al Hassania University

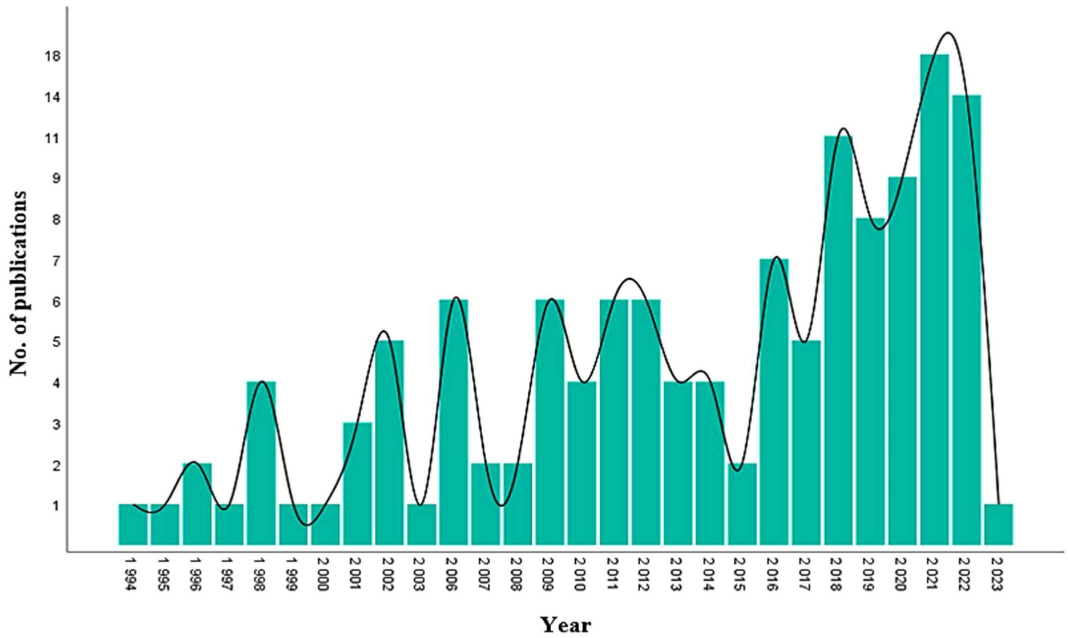

FIGURE 3
Annual number of publications related to the search topic from Scopus and WOS and Google scholar, 1994 – 2023.

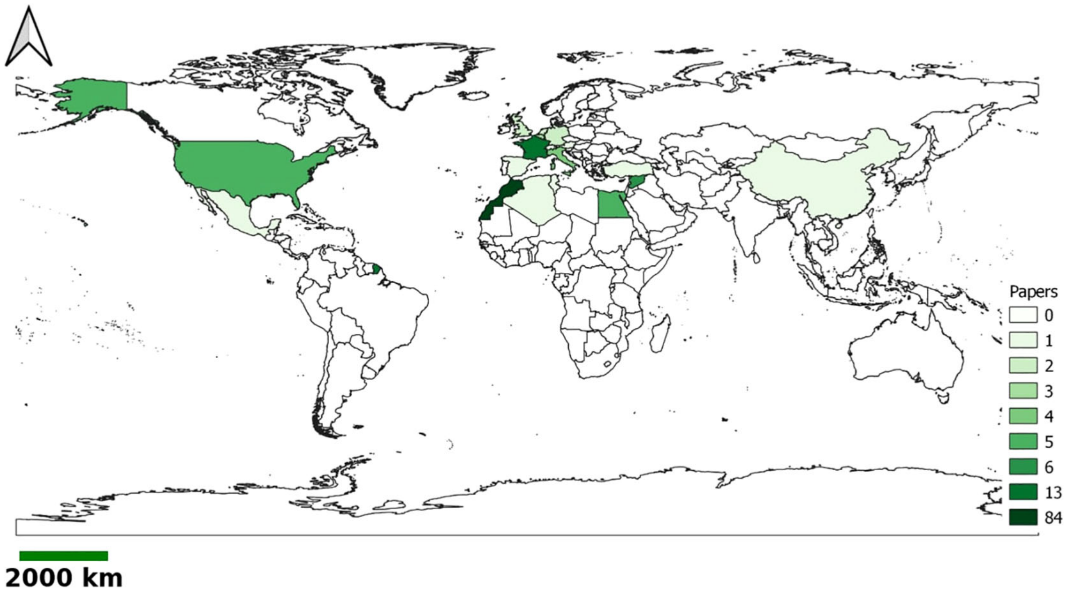

FIGURE 4
Affiliation of lead authors in terms of publications.

and Chouaib, Doukkali University, had two lead authors listed for each institution. Lastly, the Faculty of Settat, University Mohamed Premier I, the Agency for Agricultural Development, and the FAO, Morocco, made valuable contributions with one publication each. This indicates the diverse range of organizations contributing to the research output in Morocco. Generally, many institutions are involved in the research, indicating the diverse range of organizations interested in the subject topic in Morocco.

3.2 Key crops studied

Literature reveals the predominant focus on cereals, which account for 72% of the crops studied (Figure 6). Wheat constitutes 54% of all cereal crops studied and 39% of all crops investigated. It is followed by barley at 20% of cereals and 14% of all crops, while maize represents 9% of cereals and 6% of all crops. Oat, quinoa, rice, triticale and sorghum contribute to smaller shares (1 -

3%) of cereals and all crops. The significant attention given to wheat signifies its importance in Moroccan agriculture, serving not only as a staple food but also as a major source of livelihood. Legumes received notable attention, accounting for 21% of the crops investigated. Chickpea accounts for 22% of legumes and 5% of all crops, followed by faba-bean at 19% of legumes and 4% of all crops. Lentil, beans, pea, alfalfa, and vetch hold varying proportions within the legume category, ranging from 17% to 4% of legume crops and 4% to 1% of all crops. It is worth noting that this work focuses more on grain crops, particularly seeds, than other plant parts. Consequently, vegetables such as onions, potatoes, and sugar beet account for only 4% of the studied crops, while trees, specifically olive, make up the lowest proportion (2%) in this study.

3.3 Crop yield drivers

This review revealed several qualitative and quantitative crucial drivers that influence some crop yields in Morocco, classified into two main categories: climatic and non-climatic drivers.

3.3.1 Climatic drivers

A total of 96 studies examined the impact of 11 key climate-related factors on agricultural production (Figure 7). Precipitation emerged as the primary driver in 51 studies, accounting for 15.6% of the analyzed literature. The hydrological conditions in the country are mainly dependent on distribution of precipitation (Salih et al., 2022). Temperature, the second most influential meteorological element, was identified in 20(6.1%) studies, while sea surface temperature was mentioned in 3 studies (0.9%). Moreover, 8 (2.4%) observations were associated with drought, 4(1.2%) with radiation, 2(0.6%) with photoperiod, 2(0.6%) with CO_2 levels, and 1 (0.3%) each with storms and winds. In the studies analyzed, global warming was mentioned in 1 study, accounting for 0.3% of the total. Other climate influences, such as teleconnections namely El Nino - La Nina Oscillation (ENSO), North Atlantic Oscillation (NAO) and the Scandinavian Pattern (SCA), were mentioned in 3 (0.9%) studies.

3.3.2 Non climatic drivers

We identified 22 overarching drivers, both biophysical and socio-economic factors that exert the notable influence on crop production (Figure 7). Irrigation emerged as the most prominent, accounting for 32(9.8%) studies, ranking second only to precipitation due to its crucial role in sustaining crop production in the semi-arid and desert regions (Badraoui et al., 1998). Mineral and organic fertilization, along with the fertilizing impact of CO_2, received considerable attention, comprising 21(6.8%) and 2(0.6%), respectively, highlighting their substantial contribution to crop yield. Technical efficiency, encompassing factors such as mechanization, labor, human development, and technological progress, accounted for 19(5.8%) studies. Water-related challenges were identified in 20(6.1%) studies, considering that agriculture consumes over 78% of mobilized water (Lionboui et al., 2019). Five (5) studies recognized evapotranspiration as a significant constraint to agricultural production. Soil properties, including type, erosion,

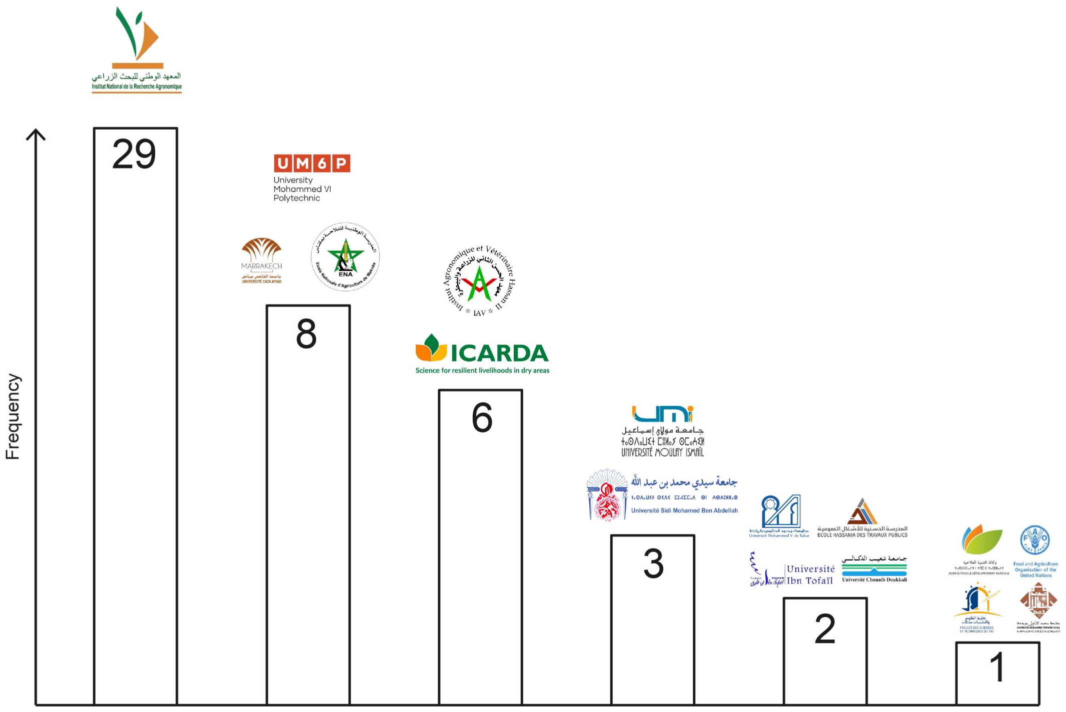

FIGURE 5
Distributions of Moroccan universities in terms of publications.

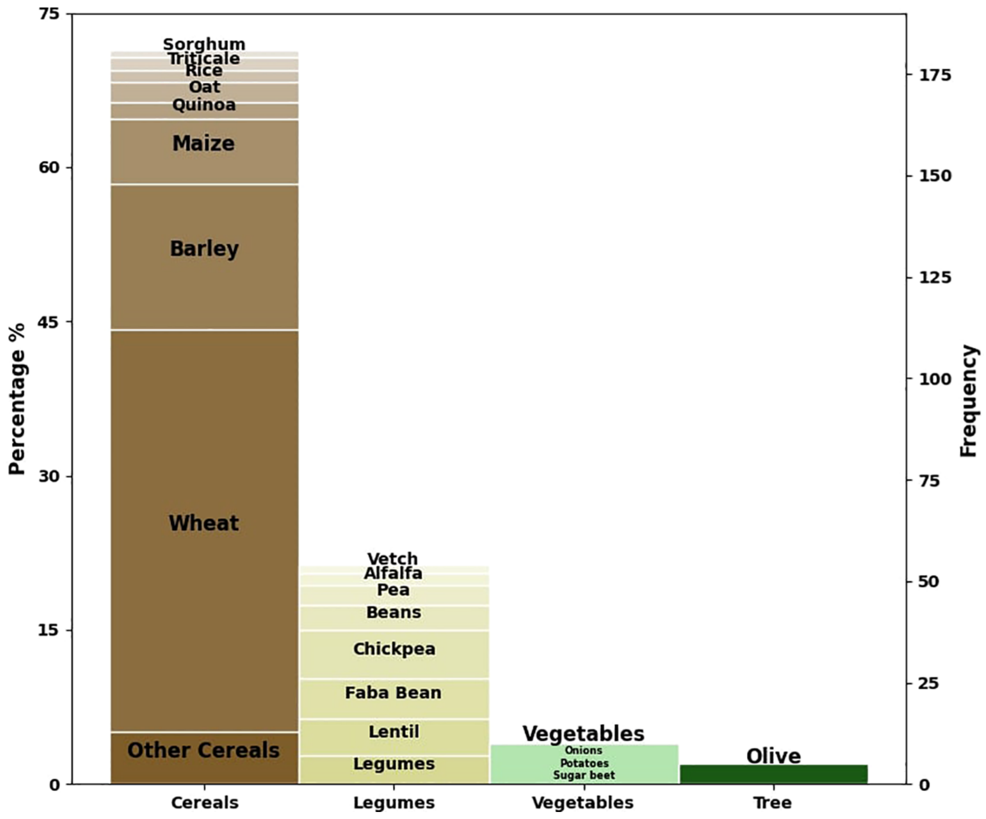

FIGURE 6
Frequency of key crops studied in this research.

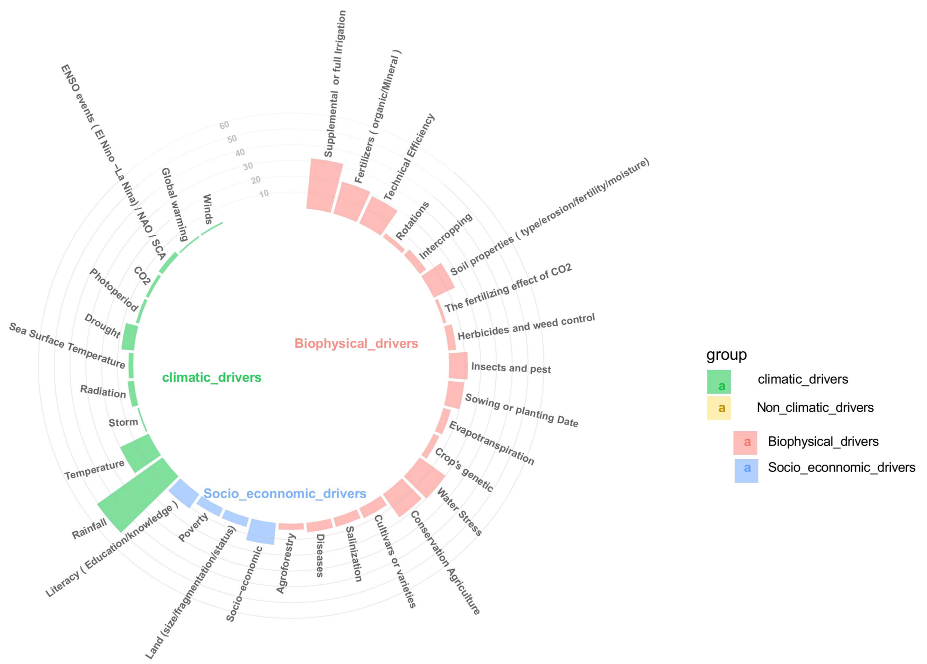

FIGURE 7
Frequency of the main drivers likely to influence crop yields in Morocco.

fertility and moisture, were found to influence the agricultural sector in approximately 15(4.6%) of conducted studies. Conservation agriculture emerged as a potential strategy for yield enhancement, as evidenced by 18(5.5%) studies. Furthermore, intercropping, rotation, and agroforestry consistently appeared as drivers for increasing crop yields across multiple studies, accounting for 5(1.5%), 3 (0.9%) and 4(1.2%) of the studies, respectively. The genetics and cultivars of crops were identified in 4(1.2%) and seven studies (2.1%), respectively. This highlights their crucial role in addressing the effects of seasonal changes on agricultural yields.

Salinization negatively impacted crop yields, as indicated by 6 (1.8%) studies. The studies are conducted in coastal areas of Morocco, reflecting the growing salinity of groundwater and soils. Further, various biophysical determinants, including sowing or planting date, herbicides and weed control, diseases, insects and pests, with occurrences of 10(3.1%), 5(1.5%), 6(1.8%), and 12(3.7%) studies, respectively, were identified. Socio-economic drivers, such as income, capital, age, infrastructure, insurance, self-sufficiency, health, population density, transportation, public aids, and research efforts, as well as literacy and poverty, land characteristics were commonly reported across the extensively studied regions of Morocco, with occurrences of 14(4.3%), 11(3.4%), 6(1.8%) and 6 (1.8%) studies, respectively.

Figure 8 illustrates a system of interconnected recommendations derived from a comprehensive review of factors influencing agricultural practices. Each node represents a distinct recommendation, such as 'Conservation Agriculture, Optimizing Irrigation,' and 'Balanced Fertilization.' The connections between nodes indicate potential relationships or dependencies among these recommendations, providing a visual representation of the complex and interrelated nature of agricultural strategies.

4 Discussion

This review on the drivers of crop yields in Morocco aims to position itself within the broader scientific discourse while addressing the challenges associated with the methodology employed in previous studies. The work seeks to provide a comprehensive understanding of the dominant factors influencing crop productivity in Morocco. It contextualizes its findings within the regional and global agricultural context, comparing them with studies conducted in similar agroecological conditions. It is important to acknowledge the challenges associated with data availability, the dynamic nature of the agricultural sector and methodological limitations. This review strives to enhance the reliability and relevance of its findings, contributing to evidence-based policy interventions and sustainable agricultural practices in Morocco.

Results show that the majority of the 135 studies analyzed between 1990 and 2024 are peer reviewed, demonstrating the concerted efforts of Moroccan scientists and their associates towards standardizing research practices and enhancing its credibility. Forty (40) articles were grey literature. This growing reliance on grey literature calls for careful evaluation of its substance, but its relevance should be acknowledged.

Moroccan institutions surpassed international ones in involvement in the country's agricultural research. This signifies their active involvement and leadership in addressing the country's agricultural challenges. The most studied crops in the review were cereals, with wheat being the dominant. This emphasis on wheat is justified by its crucial role in ensuring food security and the country's economic stability. An additional salient aspect concerns the characterization of the crop yield determinants in Morocco, which are divided into two categories, namely climatic

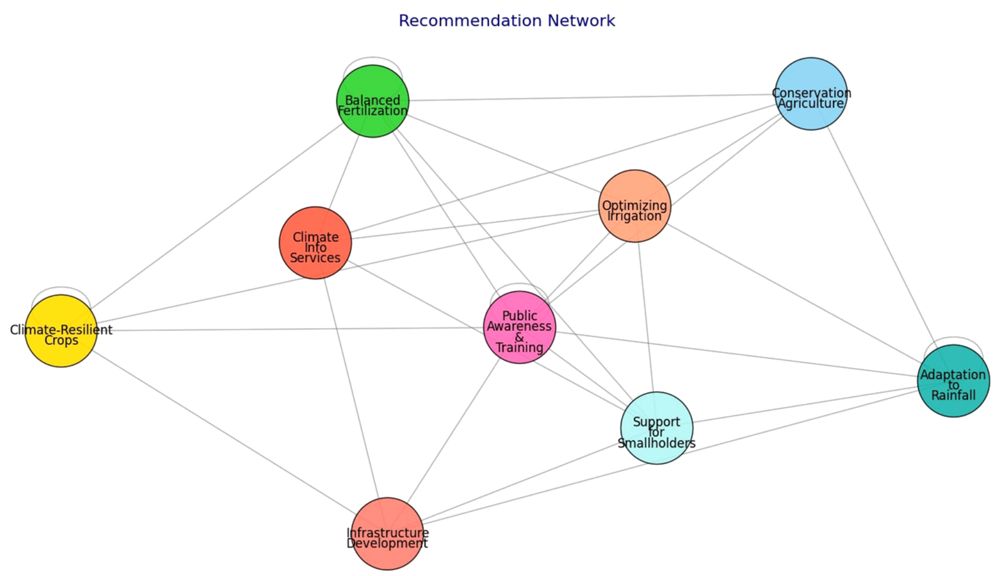

FIGURE 8
Interconnected strategies in this review.

and non-climatic attributes. The preponderance of reported and influential factors comprises rainfall, irrigation, fertilization, temperature, technical efficiency, soil properties, crop management, farm characteristics, economics, politics and institutional factors. Table 2 includes a summary, presenting the climatic and non-climatic factors critically analyzed by the authors, along with key publications and proposals to aid institutions and readers in improving agronomic practices. The following sections offer a detailed account of the main crop yield drivers, their impact, how Morocco addressed these drivers, some of the solutions implemented to surpass the negative outcomes, and the challenges that remain.

While this review identifies numerous drivers affecting crop yields in Morocco, their relative sensitivity to challenges varies.

TABLE 2 Climatic and non-climatic factors impacting agriculture in Morocco.

Category	Key Drivers	Impact on Agriculture	Key References	Recommendations for Institutions and Readers
Climatic Drivers	Precipitation	Primary driver of crop yields. Variability significantly affects rainfed agriculture; excessive or deficient rainfall leads to reduced yields or crop failure.	Balaghi et al. (2013), Salih et al. (2022), Verner et al. (2018)	Promote water conservation techniques, optimize irrigation schedules, and develop drought-resilient crops.
	Temperature	Rising temperatures exacerbate water deficits, shortening growing seasons and reducing yields.	Verner et al. (2018), Bouras et al. (2019), Hadria et al. (2006)	Develop heat-resistant crop varieties and optimize planting dates to mitigate temperature-related yield losses.
	Drought	Severe droughts lead to significant reductions in cereal production, with cascading socio-economic impacts.	Skees et al. (2001), Sraïri (2017); Bouras et al. (2020)	Enhance drought monitoring systems and invest in supplemental irrigation systems.
	Extreme Weather Events	Floods and storms affect yields by damaging crops and soil structures.	Hakam et al. (2023), Ouraich and Tyner (2014)	Develop infrastructure to manage extreme weather impacts, such as drainage systems and windbreaks.
Non-Climatic Drivers	Irrigation	Key to sustaining agriculture in arid regions; inefficiencies in irrigation practices reduce productivity.	Bouazzama et al. (2012), Lionboui et al. (2019)	Expand drip irrigation and invest in farmer training on water management practices.
	Soil Properties	Erosion, salinity, and fertility loss negatively impact productivity, especially in irrigated areas.	Badraoui et al. (1998); Bannari et al. (2008); El Hamdi et al. (2022)	Encourage soil conservation practices, organic amendments, and biostimulant use to enhance soil health.
	Fertilization	Essential for crop yields; improper use leads to environmental pollution and nutrient imbalances.	Ryan et al. (2009a); Ryan et al. (2009b); Gharous and Boulal (2016); Lazali et al. (2021)	Promote balanced fertilizer use and support farmers with precision agriculture technologies.
	Crop Management Practices	Sowing dates, conservation agriculture, and rotation systems significantly influence yield outcomes.	Mrabet et al. (2012); Tafoughalti (2018), Yigezu et al. (2019)	Advocate for conservation agriculture, early sowing, and diversified crop rotation practices.
	Socio-Economic Drivers	Aging farmers, Poverty, Literacy, gender disparities, small farm sizes, and limited access to technology hinder agricultural efficiency.	Verner et al. (2018), Bishaw et al. (2019); Harbouze et al. (2019)	Provide equitable resource access, promote gender inclusion, and invest in capacity-building initiatives.
	Crop Varieties and Genetics	Adoption of high-yield and stress-tolerant varieties enhances resilience to climatic and non-climatic challenges.	Nsarellah et al. (2011), Yigezu et al. (2021a); Bishaw et al. (2019)	Improve seed systems to ensure access to high-yield and resilient varieties.
	Institutional and Policy Frameworks	Policies like the Green Morocco Plan and Green Generation Strategy address modernization and sustainability but have implementation gaps.	Kmoch et al. (2022); Lambarraa et al. (2021); Verner et al. (2018)	Strengthen policy frameworks to support smallholder farmers and incentivize sustainable practices (Insurance, market access, smart agriculture…)

Bold values represent the main category classifications (Climatic Drivers and Non-Climatic Drivers) to distinguish them from individual key drivers.

Precipitation emerges as the most influential factor due to its significant role in rainfed agriculture and its susceptibility to climate variability. This is followed by irrigation, which mitigates water stress in arid and semi-arid regions but faces challenges of resource depletion and management inefficiencies. Temperature ranks third, with rising trends exacerbating water deficits and impacting crop phenology. Socio-economic factors, including access to fertilizers, technical efficiency, and institutional support, are critical but often constrained by financial and knowledge barriers. Among non-climatic drivers, conservation agriculture and soil management practices offer long-term resilience but require initial investments and policy support. Prioritizing these drivers based on their sensitivity allows stakeholders to allocate resources effectively, emphasizing strategies like improved irrigation efficiency, rainwater harvesting, and promoting adaptive crop varieties to combat the immediate impacts of climate variability.

4.1 Climatic drivers

Weather patterns are a major factor in determining land use. Agricultural productivity in Morocco exhibits significant regional variation due to the diverse and changing climatic conditions experienced across the country (Requier-Desjardins, 2010; Ait Houssa et al., 2016). Extensive research has revealed a range of climatic factors, including rainfall, temperature, drought, storms, radiation, photoperiod, CO_2 levels, wind patterns, and sea surface temperature, all of which exert a notable influence on crop yields.

4.1.1 Rainfall

Rainfall is widely recognized as the most critical determinant of agricultural productivity. Most of Morocco's farming occurs in the north and central-west, areas with relatively highly variable rainfall, differing from moist coastal regions, rain and snow-fed mountains, and the drier southern and eastern desert (Verner et al., 2018). According to the Ministry of Agriculture (2016), only 10% of Morocco receives over 50 mm of annual rainfall. According to Corbeels et al. (1998), there is a discernible pattern of higher crop yields in areas recording up to 500 mm of seasonal rainfall. Indeed, crop yields are impacted by the interannual fluctuation and spatial variability of precipitation (Ministry of Agriculture, 2016; Hadri et al., 2021). This impact of climate change-related hazards on agricultural productivity is most pronounced in rainfed agriculture, due to its high sensitivity to spatio-temporal rainfall variability (April et al., 2010; Maroc, 2016; Hadri et al., 2021). The vulnerability of rainfed agriculture to environmental fluctuations is more evident than in irrigated agriculture, where human intervention can alter dynamics and outcomes (Mourad et al., 2017; Hadri et al., 2021).

The country experienced several years of unfavorable climatic conditions characterized by below-average annual rainfall between 1990 and 2004 (Doukkali, 2006). Regression models identified rainfall as a significant factor impacting cereal yields in 23 provinces, with a coefficient of determination ranging from 72% to 98% (Balaghi et al., 2008). Cereal yields peak during the years with good rainfall patterns, reaching 50-60 qx/ha as seen in 2006 and 2012 when rainfall exceeded 550 mm. In contrast, during years with poor rainfall such as 2004/2005 that recorded with less than 330 mm, yields dropped to below 20 qx/ha (Aux et al., 2002; Balaghi et al., 2008, 2013; Maroc, 2016). Highlighting the variability in productivity, a Chichaoua-Mejjate study between the years 2010-2011 and 2014-2015 showed that cereal cultivation spanned 129,070 hectares during the rainy 2014-2015 year, compared to just 45,000 hectares in the dry year of 2010-2011 (Hadri et al., 2021). Moreover, yields were strongly influenced by rainfall, with a considerable increase in a wet year (6.6, 7.4, and 5.3 quintals/ha for durum wheat, soft wheat, and barley, respectively) compared to a dry year (0.30, 0.03, and 0.26 quintals/ha, respectively). In the Meknes region, variability of rainfall at monthly, seasonal, and annual scales over 15 years, revealed that the wheat yield varied greatly, ranging from 210 to 4500 kg/ha, with a coefficient of variation of 52% (Tafoughalti, 2018). Unlike in Skoura (the oasis), 43% of the surveyed farmers reported that the rainy season was shorter with a delayed onset and an abrupt and premature end before crop maturity (Aziz and Elquaoumi, 2016). Rainfall during the tilling and stem elongation stages of cereal growth is a crucial factor in determining yield (Karrou and Oweis, 2014). A decrease in precipitation during autumn could cause a delay in sowing and a shift in the growing season by up to two months, noting how farmers usually start sowing their crops following the first rain (Bouras et al., 2019). Consequently, farmers' uncertainty about rainfall leads to unpredictable yields and reduced spending on pest control and fertilization, exacerbating the impact of drought (Aït El Mekki, 2006; Aziz and Elquaoumi, 2016).

In Kenitra province, excessive rainfall, especially between 2008 and 2010, caused floods that affected cereal yields. The combination of high precipitation rates, limited water infiltration, and flat terrain with well-developed soils contributes to this particular phenomenon (Hakam et al., 2023). Consequently, these climatic challenges have significant implications for the country's overall economic growth.

4.1.2 Temperature

The temperature rise exacerbates water deficits, which further diminishes agricultural yields. Morocco recorded a significant increase in the annual mean temperature of approximately 0.5°C/decade since around 1970 (Verner et al., 2018). This rate of temperature increase significantly exceeds the global average trend of around 0.15°C per decade during the same period. Studies (e.g., Balaghi et al., 2008; Bouras et al., 2019) found that warmer temperatures led to reduced grain yield, while CO_2 enrichment resulted in increased yield at all temperature levels. The physical crop growth model combined with statistical model output agrees with previous research on yield variability, affirming the positive influence of rainfall and the adverse impact of storms and high temperatures. Temperature and storms independently contribute negatively to the explanation of cereal yield, with respective relative weights of 32% and 35% (Lehmann et al., 2020). Furthermore, the use of the CROPWAT tool revealed that the main irrigated crops in the Gharb region experience an increase in water demand as a consequence of rising temperatures (Aux et al., 2002). Using AquaCrop model, Bouras et al. (2019) revealed that without considering the fertilizing effect of CO_2, wheat yields show a decrease ranging from 7% to 30% due to rising temperatures and changes in precipitation. Hadria et al. (2006) used the STICS Model to highlight the crops' predominant sensitivity to temperature, showcasing two distinct effects: accumulated crop temperatures regulate the occurrence and duration of the reproductive phase, and temperatures exceeding 32°C hinder grain filling during reproduction.

4.1.3 Drought

Regional differences in drought resilience are evident, with the northern region exhibiting higher adaptability owing to its cultivation of a wide range of crops, including fruit trees, vegetables, and small grain cereals. The southern region is characterized by desert-like conditions, with limited agricultural activities except in oases and greenhouses, rendering it less vulnerable to climate variability compared to other major regions (Azzam and Sekkat, 2005; Verner et al., 2018).

Studies (e.g., Verner et al., 2018; Bishaw et al., 2019) supports the observation that the timing of soil tillage, occurring between August and November, significantly impacts rainfed cereal production, underscoring the vulnerability of this sector to droughts. Several instances further illustrate the detrimental consequences of droughts on crop production. For instance, cereal production plummeted from 9.5 million tons in 1994 to 1.6 million tons in 1995 due to drought (Corbeels et al., 1998; Skees et al., 2001). Similarly, the drought in 2005 led to a 50% reduction in national cereal production (Balaghi et al., 2013). Moreover, the impact of droughts was the most severe in 2007, with a staggering 76% decline in wheat production compared to the previous year (Schilling et al., 2012). Water stress, resulting from drought conditions, has been found to influence the leaf thickness and anatomical characteristics of Moroccan durum wheat varieties (Assem et al., 2017). The vulnerability to drought is also observed in irrigated cereal, fodder, and vegetable crops in certain irrigated areas, irrespective of modern or traditional irrigation schemes (Meliho et al., 2020). Consequently, these challenges affected the country's overall economic growth, which was evident during the acute winter drought of 2016, the GDP growth plummeted to less than 1.5%, in stark contrast to the 4.8% growth observed in 2015 (Sraïri, 2017).

4.1.4 Other climate-related and atmospheric variables

The implications of other diverse climate events in Morocco have demonstrated pronounced effects on crop yields, showing the intricate relationship between climatic variations and agricultural outcomes. Studies focusing on the projected increase in atmospheric CO_2 concentration have revealed significant enhancements in wheat yield across various scenarios and timeframes (Aux et al., 2002; Bouras et al., 2019). This phenomenon can be attributed to augmented photosynthesis rates, resulting in elevated plant productivity and improved water efficiency. However, findings regarding the improvement of yield under climate change following CO_2 assimilation remain inconclusive, as the catalytic effect can also transform into an inhibitory effect (Aux et al., 2002). Additionally, sunlight exposure plays a crucial role in the development and growth of crop plants, thereby exerting a strong influence on crop yield formation (Aux et al., 2002).

Extreme weather events in Morocco have led to notable decreases in cereal yields by 50-75% in dry years and 10% in normal years due to global warming (Ouraich and Tyner, 2014; Verner et al., 2018; Aoubouazza et al., 2019). While the impacts of ENSO on droughts in Morocco during 2015-2016 were limited, other teleconnections, particularly the NAO and the Mediterranean Oscillation (MO), exerted more significant effects. El Niño events pose a high probability of substantial yield reductions exceeding 50% for wheat in northern Africa (Egypt and Morocco) and corn in various parts of Africa. The NAO and SCA patterns demonstrated significant correlations with wheat yields during distinct growth stages, with NAO exerting influence in the early growth phase (December) while SCA affects yields in January and February (Jarlan et al., 2013; Hakam et al., 2023). Overall, these findings underscore the complex and interconnected influences of various climate phenomena on crop production. The intensified climate variability leads to more severe drought conditions, imposing adverse effects on rainfed crops.

4.2 Non-climatic drivers

4.2.1 Water management

The heightened water scarcity is the primary driver for adaptation efforts among Mediterranean farmers, given its recognized status as a major threat to irrigated agriculture (Fader et al., 2016; Harmanny and Malek, 2019). Moreover, the depletion of groundwater resources has become a growing concern in many parts of the country. Surface-water management projects have resulted in a transition from traditional water management to farmer-controlled groundwater supply (Heidecke et al., 2010; Sraïri, 2017; Sraïri, 2018). However, this shift has led to a significant decline in groundwater levels, adversely affecting crop yields in certain areas (Breuer, 2007; Kuhn et al., 2010; Schilling et al., 2012).

The challenges posed by water scarcity are particularly pronounced in private irrigation zones and small-scale systems reliant on groundwater (Bouazza et al., 2002). Consecutive negative water balances have resulted in the non-renewal of these resources, leading to depletion, overexploitation, saline intrusion and fertilizer pollution. It is anticipated that some of these areas may ultimately revert to their original non-irrigated state (Aux et al., 2002). Uncontrolled pumping practices in oasis zones, coupled with a limited assessment of groundwater potential, present a significant risk of irreversible resource depletion. Additionally, the persistent use of gravity irrigation techniques contributes to substantial water wastage (Aziz and Elquaoumi, 2016). Furthermore, the Sebou River in the Gharb region is heavily polluted by domestic and industrial wastewater discharges, imposing a major constraint on agricultural production for local farmers (Fornage, 2006). According to Aziz and Elquaoumi (2016), farmers require support and guidance from technical services, including the provision of new technologies and resistant crop varieties to address these challenges.

Simulation tools like the WOFOST model have proven effective for improving water management at the farm level (Bregaglio et al., 2015). They help identify yield gaps and optimize water use efficiency by analyzing factors like crop cycle management, water supply, and fertilization levels. For instance, an average yield gap of 5.35 t/ha has been observed between potential and observed yields in Morocco, highlighting the significant potential for improvement through better water and crop management practices (Dewenam et al., 2021; Bouazzama et al., 2012). These findings underscore the importance of integrating advanced simulation models to enhance water use efficiency and address water management challenges effectively (Bouazzama et al., 2012).

4.2.2 Soil

Agricultural productivity is greatly influenced by soil type, with deep and well-buffered soils demonstrating superior drought tolerance and yielding higher outputs compared to shallow, rapidly depleting soils (Maroc, 2016). Furthermore, the alarming fact remains that erosion has already afflicted 75% of Morocco's arable lands, highlighting the urgent need for remedial measures (Morocco, 2011). Moroccan soil exhibits a water capacity of less than 20 mm for thin soils and 10 mm for very deep soils (Ministry of Agriculture, 2016). The combination of high evaporative demand and the presence of shallow, eroded calcareous soils (over 80%) intensifies the scarcity of soil moisture (El Mourid and Karrou, 1996). Bouras et al. (2020) highlighted the significant influence of soil moisture anomalies and adverse weather conditions on vegetation decline and subsequent yield losses during the 2011–2012 and 2015–2016 drought periods (Bouras et al., 2020).

The increasing global salinization poses a significant threat to arid and semi-arid regions, leading to the degradation of soils (Raja et al., 2022). In Morocco, drylands covering over 700,000 hectares face a major salinity challenge due to the overuse of surface and groundwater, coupled with agricultural intensification, resulting in soil salinity and sodicity issues (Bannari et al., 2008). Salinization affects a significant number of farms in southern Morocco, with 80% of soils in the Ouarzazate province being affected (Davis, 2006; Bannari et al., 2008). Inappropriate irrigation practices have also contributed to increasing salinization, with 35% of irrigated areas nationwide being saline (Badraoui et al., 2000). Studies show that previously non-saline soils become saline after irrigation, leading to rapid salinization and alkalization under high evapotranspiration conditions, depending on human management (Badraoui et al., 1998, 2000; Duchemin et al., 2006). In Morocco, irrigated soils can experience more than a 50% loss in productivity due to salinization (Badraoui et al., 1998). The cultivation of different crops (wheat, olive, sugar beet, alfalfa, carrots) in the Tadla plain over 24 years revealed two main factors contributing to salinization: the type of crop, which increases salinity based on unsatisfied water needs, and the gravity irrigation method associated with uneven water distribution within plots (El Hamdi et al., 2022). Wheat yield reduction of 10% due to soil salinity reached critical levels in 7 out of 49 irrigated plots, with two plots producing less than 50% of their potential yield. Within less than 5 years, 9 additional plots experienced a 10% yield reduction (Badraoui et al., 1998).

Barley is well-suited to local climatic conditions due to its tolerance to salinity and low water requirements (Aziz and Elquaoumi, 2016; Zaouaq, 2021). The salt tolerance index helps select tolerant barley genotypes, and the Tamelalt cultivar, with a salt tolerance index of 59.77%, is identified as suitable for cultivation in saline soils (El Goumi et al., 2014). Salt-tolerant forage crops such as blue panicum, sesbania, pearl millet, barley, quinoa, and triticale is recommended to overcome challenges posed by high water and soil salinity. Therefore, scaling up the cultivation of these crops is recommended in the southern regions of Morocco (Brakez et al., 2016; Hirich et al., 2021a; Hirich et al., 2021b). Furthermore, biostimulants are gaining attention as natural tools to improve soil health and enhance crop tolerance to various stresses, including salinity, by enhancing soil structure, nutrient uptake, water absorption, and phytohormone production (Raja et al., 2022).

4.2.3 Farm practices

4.2.3.1 Irrigation practices

Water scarcity is a significant constraint on agricultural development in Morocco, necessitating the use of irrigation to support crops (Badraoui et al., 1998). Implementation of central pivot irrigation systems and other techniques in arid regions has led to higher crop yields compared to rainfed conditions (Badraoui et al., 1998; Benabdelouahab et al., 2021). Drip irrigation and access to groundwater offer social benefits to farmers, allowing independence from collective irrigation networks and crop diversification (Quarouch et al., 2014). Despite progress in expanding irrigation infrastructure, many Moroccan farmers have limited access to irrigated land, resulting in poor-quality products and low yields (Verner et al., 2018). Groundwater-based irrigation systems demonstrate better water utilization compared to combined surface and underground water sources or dam water alone (Lionboui et al., 2019). However, a significant proportion of farmers lack awareness of available technologies, leading to inefficiency in farming practices (Harbouze et al., 2014). Efficient irrigation practices can bridge the yield gap caused by inadequate infrastructure. Increasing human appropriation of freshwater resources for irrigation by at least 146% would be necessary to close this gap, but the current availability and distribution of irrigation technology make it unlikely to achieve sustainable crop yield improvements (Davis et al., 2017). Additionally, the conversion to drip irrigation, promoted through public policies, may not necessarily lead to expected water savings compared to traditional flooding methods due to factors such as improper use, soil washout, expanded irrigation to previously unirrigated fields, and intensified cropping (Bouras et al., 2019).

Supplementary irrigation is crucial in overcoming the adverse effects of drought, especially in semi-arid regions like Marrakech and Agadir (Boutfirass et al., 2005; Abderrazzak et al., 2011). Water conservation techniques and supplemental irrigation are necessary to stabilize and optimize cereal production in southern regions facing severe climatic deficits (Abderrazzak et al., 2011). Studies have shown that supplemental irrigation enhances grain yield, with varying efficiency depending on the water regime and specific growth stages (Abderrazzak et al., 2009; Daroui et al., 2011). Irrigating wheat with intervals of 15 to 21 days optimizes water and fertilizer uptake (Ichir et al., 2003). Quinoa yield is significantly higher undertreated wastewater irrigation compared to rainfed conditions (Hirich et al., 2012). For silage maize, irrigation during the linear growth phase and prioritizing its irrigation over other crops is recommended (Bouazzama et al., 2012). Partial irrigation has shown positive effects, with 100mm of supplemental irrigation potentially saving cereal crops from fatal drought and achieving significant yields (Aux et al., 2002). Crop modeling has demonstrated the potential to schedule irrigation based on water deficit thresholds, improving grain yield and water productivity (Benabdelouahab et al., 2016; Toumi et al., 2016).

The AquaCrop model is a suitable tool for simulating water stress effects and optimizing irrigation management under semi-arid conditions (Benabdelouahab et al., 2016; Toumi et al., 2016). Thresholds for root zone water depletion have been identified to improve wheat irrigation management (Toumi et al., 2016). Simulation analysis using APSIM has shown that early crop establishment through 40mm of supplementary irrigation at sowing enhances average grain yields (Hadria et al., 2007). Moreover, restrictive irrigation strategies, such as applying 50mm of irrigation, benefit faba bean productivity and soil fertility in Morocco and the MENA region (Marrou et al., 2021).

4.2.3.2 Fertilization

Understanding soil fertility is important for optimizing fertilizer use. The same influences crop choice. For instance, chickpea cultivation enhances soil nitrogen content through symbiotic nitrogen fixation, contributing to soil fertility (Lazali et al., 2021). Despite significant advancements, the actual impact on yield increase at the farm level remains suboptimal due to prevailing soil issues. Thus, the management of fertilizer is essential for achieving optimal yields. In Morocco, the use of fertilizers, particularly nitrogen (N), is a significant factor in determining the level of intensification of cereal production, second only to water availability (Abderrazzak, 2013; Savin et al., 2022). In various regions of Morocco, nitrogen fertilizer positively influenced biomass and grain yields in cereals like barley, bread wheat, durum wheat, and triticale (Ryan et al., 1998, 1997; Ryan et al., 2009a). However, the application of high amounts of nitrogen during dry years and its deficiency during wet years can lead to substantial declines in cereal yields. Thus, careful management of water and nitrogen is necessary to avoid losses (Abderrazzak, 2013; El Mourid and Karrou, 1996; Karrou, 1996). Studies conducted in different regions of Morocco have highlighted the challenges that farmers face in terms of fertilizer application and nutrient management. For instance, in the Souss-Massa region, farmers lack reliable fertilizer standards and data on crop water consumption, leading to problems such as soil depletion, diseases, residues, and water scarcity (Bouzoubaâ et al., 2009). Similarly, in the Saïs region, field trials have shown that the optimal amount of nitrogen fertilizer needed for maximum grain yield depends on rainfall availability, with 120 kg N/ha being the most effective in a year with sufficient rainfall (Abderrazzak, 2013).

In addition to nitrogen, the adequate application of other essential nutrients such as phosphorus (P), potassium (K), and silicate is crucial for crop production. Research has shown that phosphorus fertilization has a positive impact on biomass and grain yield for various cereal crops in Morocco. Barley, in particular, has demonstrated a high responsiveness to phosphorus application (Ryan et al., 1995; Gharous and Boulal, 2016). Investigations into silicate fertilization have highlighted its potential to rectify soil and climatic disparities, reduce water loss from plants and enhance internal water status (Bouzoubaâ et al., 2009). Potassium deficiency can result in reduced grain quality and yield losses in cereals (Marschner et al., 2012). For cereal crops, recommended potassium application rates range from 40 to 100 kg/ha (Gharous and Boulal, 2016). Furthermore, the incorporation of organic amendments, such as farmyard manure, in combination with mineral fertilizers, has shown promising in improving forage productivity in salt-affected lands, thus mitigating the negative effects of soil salinity on crop growth (El Mouttaqi et al., 2022). Moreover, the proper timing and rate of nutrient application, including nitrogen, phosphorus, potassium, and silicate, should be determined based on factors such as moisture availability, soil conditions, crop genotype, and seasonal variations (Ryan et al., 2009a; Ryan et al., 2009b; Cooke and Leishman, 2016). While fertigation offers advantages in terms of nutrient precision, it also poses challenges in achieving proper water and fertilizer distribution, potentially affecting crop yields. Thus, careful management of fertigation practices is necessary to ensure effective nutrient delivery and optimize crop performance (Corbeels et al., 1999; Bouzoubaâ et al., 2009; Ryan et al., 2009a).

Despite the importance of fertilizer use, its adoption by farmers in Morocco remains low (Gharous and Boulal, 2016). Various factors, including financial constraints and lack of awareness about the benefits of fertilizer application, contribute to this situation (Irhza et al., 2023). Additionally, the use of fertilizer on legumes is often neglected due to traditional beliefs that these plants can meet their nutrient requirements (Irhza et al., 2023). Overall, the application of appropriate NPK fertilizers, considering soil characteristics, rainfall patterns, and crop requirements, is essential to improve crop productivity and soil quality in Morocco. However, excessive use can lead to environmental pollution and water contamination, highlighting the importance of balanced fertilization practices (Bouzoubaâ et al., 2009). The optimization of fertilizer use efficiency, and the implementation of best management practices are crucial for sustainable agriculture in dry areas (Abderrazzak, 2013).

4.2.3.3 Conservation agriculture

Conservation agriculture practices have gained attention in Morocco due to their potential to improve agricultural productivity, soil health, and economic viability. Extensive research conducted over several years has provided compelling evidence of the benefits associated with conservation agriculture (Mrabet, 2011; Bonzanigo et al., 2016; Verner et al., 2018;

Aboutayeb et al., 2020; El-Shater and Yigezu, 2021; El Mekkaoui et al., 2021; Devkota et al., 2022; Et-Tayeb et al., 2022). The adoption of conservation agriculture particularly zero tillage, can lead to substantial yield increases in various crops (Shakhatreh, 2011; Moussadek et al., 2014; Yigezu et al., 2021b; Devkota et al., 2022; Et-Tayeb et al., 2022). Wheat production, for example, has shown yield gains of up to 43%, while barley, lentil, and chickpea have shown yield improvements of 8%, 11%, and 19%, respectively (Mrabet et al., 2001; El-Shater and Yigezu, 2021; Yigezu et al., 2021a; Devkota et al., 2022). These yield gains have been attributed to improved water infiltration, reduced soil erosion, and enhanced nutrient availability (Dimanche and Hoogmoed, 2002; Shakhatreh, 2011; Mrabet et al., 2012; Devkota et al., 2022; Et-Tayeb et al., 2022).

In addition to yield improvements, conservation agriculture has shown promising effects on soil health indicators. Long-term studies have revealed that conservation agriculture practices promote increased soil organic matter content, improved soil structure, and enhanced soil nutrient cycling (Devkota et al., 2022). This leads to better water-holding capacity, increased nutrient availability for plants, and improved overall soil fertility. These soil health benefits contribute to the long-term sustainability of agricultural systems, improving their resilience to climate variability and reducing the need for additional inputs such as fertilizers and pesticides (Mrabet et al., 2001; Shakhatreh, 2011; Moussadek et al., 2014; Devkota et al., 2022; Et-Tayeb et al., 2022).

Beyond the agronomic benefits, studies have highlighted reduced labor requirements and production costs associated with conservation agriculture practices. Furthermore, the adoption of conservation agriculture has led to higher gross margins, increased precipitation use efficiency, and reduced production expenses. These economic benefits are particularly evident in cereal-legume rotation systems, where conservation agriculture has resulted in increased system yield, total benefits, and cost savings (Magnan et al., 2011a; Mrabet et al., 2012; El-Shater and Yigezu, 2021; Yigezu et al., 2021a; Yigezu and El-Shater, 2021).

Although conservation agriculture has demonstrated its potential in research trials, its wider adoption and implementation face challenges (Aboutayeb et al., 2020). Limited awareness and access to suitable machinery, along with inadequate subsidy policies, have hindered the scaling-up of conservation practices. Promoting crop rotation and diversification, along with developing value chains and marketing systems for alternative crops, is crucial to overcoming the dominance of wheat-centric rotations. Addressing these challenges and providing necessary support, including access to resources and knowledge transfer, is essential to encourage broader adoption of conservation agriculture practices and unlock their full potential for sustainable and resilient agriculture in Morocco (Mrabet et al., 2001; Mrabet et al., 2012; Verner et al., 2018; Aboutayeb et al., 2020).

4.2.3.4 Crop rotation

The selection of crops for rotation is primarily influenced by seed availability and the needs of the farming family. According to Irhza et al. (2023), crop associations were based on ancestral knowledge and seed availability rather than the specific characteristics of plants, such as above and below-ground structures (leaves, root system, rooting depth, species compatibility, etc.). Yigezu et al. (2019) used two years of data from 1230 farm households and 2643 fields in the wheat-based production system of Morocco found that legume-cereal rotations offer clear economic advantages over monocropping. These rotations result in higher yields, gross margins, and consumption of wheat and faba beans. Devkota and Yigezu (2020) confirmed that including a legume crop (faba bean) in wheat-based systems increased the two-year gross margin by 48% compared to wheat monocropping. In drier regions or years, wheat-fallow rotation is a viable option, while wheat-fallow-lentil or barley rotations are recommended in more favorable environments. However, the lowest yield is observed when following spring chickpea, which depletes soil moisture (Maroc, 2016; Devkota and Yigezu, 2020).

4.2.3.5 Agroforestry and intercropping

Agroforestry and intercropping systems have emerged as viable strategies for sustainable agriculture, particularly in regions facing land scarcity and water limitations. The combination of perennial crops with annuals offers numerous advantages, including biodiversity conservation, diversification of production, carbon sequestration, and enhanced profitability (Daoui et al., 2014; Wahbi, 2016; Abderrazzak et al., 2018; Mouradi et al., 2018; Amassaghrou et al., 2021; Kallida et al., 2021). These systems, widely practiced in Morocco's mountainous and oasis regions, provide alternative solutions for climate change adaptation, livestock integration, erosion control, and improved resource utilization (Daoui et al., 2014). Research findings demonstrate the agronomic and economic benefits of intercropping, especially in olive-based agroforestry systems. Olive + cereals and olive + legumes associations have shown better productivity and economic results compared to monoculture systems (Amassaghrou et al., 2021; Temani et al., 2021) For example, in the 2022 growing season, barley yield in agroforestry systems reached up to 5.87 t/ha under southern intercropping and 4.46 t/ha under northern intercropping, compared to 1.19 t/ha in monoculture systems (Benalia et al., 2024). Furthermore, intercropping of vetches and peas with small grain cereals has been found to significantly impact forage yields, with oat-legumes and triticale-legumes intercrops exhibiting high and stable yields (Kallida et al., 2021). These findings underscore the potential of intercropping systems to enhance agricultural productivity, optimize resource utilization, and improve economic outcomes. However, further research and promotion are necessary to fully unlock the potential of agroforestry and intercropping practices and encourage their widespread adoption in diverse agricultural contexts. Overall, these practices offer sustainable solutions to land scarcity and contribute to the long-term viability of agricultural systems.

4.2.3.6 Sowing date

Efficient management of sowing dates plays a pivotal role in optimizing crop yields and adapting to changing climatic conditions. Extensive research using the NDVI-based approach and AquaCrop model consistently demonstrates that early sowing scenarios lead to higher wheat yields than late sowing scenarios.

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This finding is crucial for promoting equity among farmers and ensuring a more uniform distribution of crop productivity. It is important to note that altering sowing dates carries potential risks, including increased susceptibility to diseases, pest attacks, and weed development, which can have severe consequences exacerbated by climate change. Therefore, integrated analyses consider various factors, and their interactions are recommended to make informed decisions and develop comprehensive strategies for sustainable agricultural practices (Aux et al., 2002; Belaqziz et al., 2021; Amine et al., 2022).

The significance of early seeding extends beyond yield improvement, encompassing efficient water management and enhanced transpiration efficiency. Multiple simulations and experiments consistently highlight the advantages of early sowing in terms of water conservation and achieving optimal grain yield. In addition, studies reveal a strong correlation between soft wheat and hard wheat in the period from January to March, emphasizing the importance of aligning appropriate adaptation strategies during this critical phase for successful wheat production. Implementing optimized sowing dates not only fosters equity among farmers but also minimizes spatial heterogeneity, leading to improved irrigation scheduling and resource utilization. Such approaches can significantly reduce the applied irrigation water by more than 40%, thus providing valuable insights and recommendations for irrigation managers and farmers (Heng et al., 2007; Toumi et al., 2016; Tafoughalti, 2018; Belaqziz et al., 2021; Dewenam et al., 2021; Taaime et al., 2022). So, the careful selection of sowing dates emerges as a cornerstone of success in the agricultural landscape, paving the way for abundant harvests and contributing to the overall welfare of farming communities.

4.2.3.7 Technological advancement and uptake

The low adoption of agricultural technologies in developing countries like Morocco poses a significant challenge to development efforts. Limited technology adoption hinders the expansion of agricultural production and exacerbates inefficiencies. For example, Morocco faces substantial inefficiencies in its farming operations, with technical efficiency estimated between 35% and 50% (Hassine, 2007; El Ansari et al., 2016; El Ansari et al., 2020). During wet years, farmers fail to utilize sufficient inputs such as irrigation water, fertilizers, and pesticides, leading to suboptimal yields (Pala et al., 2011). Several strategies such as planting early to semi-early cultivars, implementing early weed control, optimizing nitrogen application, and employing water conservation practices have been identified to enhance crop yields. In semi-arid areas like Morocco, water conservation is critical for improving wheat productivity. Methods such as no-tillage farming, residue management, and fallowing have been shown to conserve soil moisture, reduce evaporation, and improve water retention. By adopting these techniques, yield can be increased and stabilized. However, significant yield gaps still exist in both rainfed and irrigated environments in Morocco. Addressing these gaps presents opportunities for improving wheat water productivity in semi-arid areas (Karrou et al., 2008).

Insufficient infrastructure and limited access to agricultural inputs, such as seeds, fertilizers, pesticides, and farm equipment, hinder technological progress in the agricultural sector. The lack of adequate storage facilities during periods of excess production further compounds these challenges (El Mourid and Karrou, 1996). The Moroccan Ministry of Agriculture's initiatives have increased average cereal yields from 0.5 to 1.5 tonnes per hectare over the past two decades, despite regional climate variability. This improvement is due to better agronomic practices and increased investments in agricultural infrastructure and technology (Mamassi et al., 2023). Mechanization plays a critical role but needs to suit specific conditions. Subsidies for mechanization can homogenize landscapes and eliminate small farms (Van Zanten et al., 2014). Moreover, inadequate investment in research and technology transfer hampers progress in cereal production, and while the GMP promotes efficient practices in large agribusiness farms, it has limited specific support measures for rainfed systems (El Mourid and Karrou, 1996; Sraïri, 2017; Baccar et al., 2019).

4.2.4 Socio-economic drivers

Although the Moroccan population relies heavily on agriculture for food and livelihood, the sector faces numerous socioeconomic constraints. The majority of farmers are aging and have limited access to modern technologies and resources (Bajeddi, 2000; Verner et al., 2018). The average age of farmers is around 52 years, with a significant proportion being 65 years or older with low uptake of new technological innovations (Bajeddi, 2000). The legal status of farms and fragmentation issues further hinder investments and productivity improvement (Aït El Mekki, 2006). Most production units operate on small farms, with an average area of less than 5 hectares, making it challenging to overcome these unfavorable factors (Aït El Mekki, 2006). These small farms often exhibit low productivity and limited market integration, and they predominantly rely on rainfed production systems, have limited access to modern technologies, and lack technical know-how (Verner et al., 2018). As a result, they are highly vulnerable to recurrent droughts and typically produce low-value agricultural commodities, such as wheat and barley, for which government subsidies and market protection are provided (Verner et al., 2018). Moreover, women's contributions to subsistence farming are often unpaid and unrecognized, further exacerbating gender disparities in the agricultural sector (Verner et al., 2018; Baruah and Najjar, 2022). One major obstacle woman face in farming is their limited access to resources such as land, fertilizer, information, machinery, and labor (Bishaw et al., 2019). The FAO (2011) highlights that providing women with equitable access to these resources could reduce global hunger by up to 17% and increase food production by up to 4%, underscoring the importance of addressing gender inequalities in agriculture.

Farmers also struggle with rising input prices and stagnant or declining commodity prices (Magnan et al., 2011a). This economic barrier further challenges the profitability of agricultural activities and affects the farmers' income and livelihoods (Magnan et al., 2011b). Moreover, small farmers face additional constraints such as marginalized land, land titling issues, land fragmentation, unpredictable rainfall, limited market access, and limited farmer organization (Verner et al., 2018). These factors collectively contribute to the overall challenges faced by farmers in the region. Moreover, the Moroccan agricultural system shows a significant imbalance between irrigated and rainfed areas, with limited investments and support for the latter (Sraïri, 2017). The transition to high-value crops for achieving self-sufficiency poses an opportunity cost, impacting revenue (Magnan et al., 2011a).

Despite government subsidies for cereal seeds, small farms benefit less from initiatives like drip irrigation due to their size and limited cooperation with neighboring farms (Jobbins et al., 2015). Overall, addressing these challenges requires a holistic approach, including climate adaptation strategies, improved education and training, enhanced access to resources, and equitable distribution of opportunities in the agricultural sector (Giuliani et al., 2017; Verner et al., 2018; Harmanny and Malek, 2019).

4.2.5 Adaptive capacity

Assessing the adaptive capacity of farmers is essential in understanding their ability to adapt to changing conditions (Epule et al., 2021; Achli et al., 2022). The adaptive capacity index, developed by Swanson et al. (2007), considers six determinants: economic resources, technology, knowledge and skills, infrastructure, institutional and equity. Grasso and Feola (2012) assessed adaptive capacity in different Mediterranean regions, and their findings revealed that Morocco exhibited a low adaptive capacity, performing poorly across all six aforementioned determinants, relative to other countries (Grasso and Feola, 2012; Hossard et al., 2021). Morocco can be considered to have the lowest generic adaptive capacity, as the country performs poorly in terms of economic resources, human development, health, and education (Schilling et al., 2012). It is important to note that the specific adaptive capacity, which is shaped by institutional performance and the availability of knowledge and technology, is more challenging to characterize than the generic adaptive capacity.

Water scarcity significantly impacts Moroccan agriculture, which consumes over 85% of the water. While irrigation promotion aims to aid development, its water-saving effects per hectare are below expectations due to insufficient farmer training (Benouniche et al., 2014). The focus of efforts has primarily been on irrigation techniques, neglecting the necessary accompanying measures to improve farming practices (Kuper et al., 2009). The ability of farmers to adapt is influenced by various factors, both biophysical and socio-economic. Research findings indicate that farmers in less rural areas with lower poverty rates and better market access, as well as areas with higher temperatures and less rainfall, are more likely to adopt adaptive measures (Harmanny and Malek, 2019). Studies (Schultz, 1995; Doss, 2001; Wale and Yalew, 2007) suggest that the probability of technology adoption depends on farmers' ability to perceive the advantages and compatibility of new technologies with their existing socio-economic conditions. Knowledge of improved agricultural technologies, attitudes towards risk, access to information, and stability of yield and prices are significant factors influencing farmers' technology preferences (Feder et al., 1985; Kristjanson, 1987; Kaguongo et al., 1997). Moreover, technologies with lower risks tend to be more appealing to smallholders, who are typically more risk-averse (Meinzen-Dick et al., 2004; Bishaw et al., 2019).

Despite the efforts made, Morocco continues to face significant development challenges, including high poverty rates, urban-rural disparities, and low human development, especially in rural communities (Sraïri, 2017; Baccar et al., 2017). Food insecurity and poverty are closely linked in Morocco, partly due to the significant proportion of household income (around 70%) spent on food. Out of approximately 4 million people living below the national poverty line, 3 million reside in rural areas characterized by poor geographical conditions, low population density, and limited physical and social infrastructure (Harbouze et al., 2019). Challenges associated with rural poverty include inadequate farm equipment, low utilization of inputs such as improved seeds, fertilizers, and pesticides (Fornage, 2006; Harmanny and Malek, 2019). The Middle Sebou region exhibits higher poverty rates compared to the national average, characterized by larger household sizes, high illiteracy rates, and limited access to education (Fornage, 2006). Rural poverty remains a prevalent issue in Morocco, with approximately one in four Moroccans affected, compared to one in ten in urban areas. Achli et al. (2022) emphasize the role of socioeconomic factors, such as literacy and poverty rates, in shaping adaptive capacity, suggesting that improving these indicators helps mitigate the adverse effects of climate variability on cereal yields. The Fes region is particularly affected due to its dependence on cereal crops. However, partial liberalization measures in this region without accompanying support programs targeting the most vulnerable populations could result in the failure of marginal and low-productivity farms and exacerbate rural exodus (Fornage, 2006).

Relatively high illiteracy level poses a challenge for agricultural research scientists and their ability to develop and test technologies suitable for farmers facing climatic constraints. The adoption of drip irrigation, for example, is influenced by factors such as land tenure status, literacy levels, administrative processes, geographic remoteness, and gender disparities. Subsidies offered at varying percentages have proven effective in supporting small farmers on private property, but they do not eliminate access barriers for all farmers, particularly marginalized groups (Jobbins et al., 2015).

4.2.6 Varieties, cultivars, and crop's genetics

The evolution of agriculture in Morocco is marked by the integration of high-yielding crop varieties and efficient management practices, prominently impacting wheat cultivation (Bishaw et al., 2019). These strategies have enhanced yields, resistance to pests, and adaptability to Morocco's diverse climatic conditions (Ministry of Agriculture, 2016). For instance, early maturing varieties, including the semi-dwarf Mexican wheat strains, have significantly benefited drought-prone regions like

Meknes and Fes by mitigating drought effects (Zeggaf et al., 2002; Bishaw et al., 2019). Such varieties, adapted from Mediterranean germplasm, excel under Moroccan conditions and address challenges tied to climate variability. However, there has been a significant increase in the adoption of foreign wheat varieties, mainly introduced by the private sector, posing marketing challenges for new bread and durum wheat varieties developed by INRA (Bishaw et al., 2019). Concurrently, a functional seed-delivery system is crucial for the adoption of these newly developed varieties. For example, despite their high yields, chickpea cultivars face limited adoption due to consumer preference for larger seeds (Amine et al., 2022).

Overseeing variety release and registration, the National Office for Food Safety since 2010 has ensured new crop breeds meet technological, quality, and resistance standards, catering to Morocco's agroecological diversity (Ministry of Agriculture, 2016; Bishaw et al., 2019). Recent releases, like the post-2003 durum wheat varieties, stand out for their resilience against pests such as the Hessian fly and adaptability to semi-arid conditions (Nsarellah et al., 2011). Nevertheless, despite the notable strides made in crop variety development, several challenges persist. The prevalence of antiquated crop varieties, including wheat, in Moroccan fields underscores the urgency of addressing the limited adoption rates of newer varieties (Bishaw et al., 2019). Institutional factors, such as stringent variety testing protocols, power asymmetries, and flawed licensing agreements, limit access to recent varieties (Yigezu et al., 2021a). Moreover, farmers face constraints regarding the availability of up-to-date information on contemporary crop varieties and the scarcity of seeds, both of which contribute to the perpetuation of outdated cultivars (Bishaw et al., 2019). To maximize the potential benefits conferred by improved crop varieties, augmenting farmers' awareness and ensuring timely seed availability for the latest cultivars are imperative. Mitigating these constraints necessitates increased involvement of private entities in seed multiplication, revising testing procedures, implementing alternative royalty mechanisms, and fostering stronger collaborations between public research institutions and private seed companies (Yigezu et al., 2021a; Yigezu and El-Shater, 2021).

From a genetic perspective, Morocco's agricultural trajectory reveals genetic advancements boosting durum and soft wheat yields, while barley sees diminishing returns due to a preference for drier conditions (Balaghi et al., 2013). Factors like environmental context underscore the significance of genotype-environment interplays (Nsarellah et al., 2011). Modern strategies like early sowing, employing resistant chickpea genotypes, and leveraging crop simulation models enhance productivity and sustainability (Asseng et al., 2013; De Wit et al., 2013; Amine et al., 2022; Mamassi et al., 2022). Genetic innovations, from chromosomal engineering to specialized breeding for traits like root architecture, further advance wheat cultivation (El Hassouni et al., 2018; Kuzmanović et al., 2018). Embracing these integrated approaches offers a roadmap for sustainable and optimized agriculture in Morocco.

4.2.7 Insects and diseases

The environmental characteristics of Moroccan agricultural systems contribute to widespread foliar diseases (rusts, septoria…) and insect infestations (hessian fly, green bug, sowfly…), resulting in low and irregular crop and livestock production (El Mourid and Karrou, 1996). Implementing cautious interventions, particularly weed control measures, can mitigate yield losses and lead to significant yield gains (Boutahar, 1994; Awamia and Bp, 2002; Aït El Mekki, 2006). Furthermore, using natural products, such as pesticide plants, shows promise as an alternative to synthetic insecticides for protecting stored cereals against pest infestations (Lougraimzi et al., 2019). In Moroccan barley fields, net blotch is a prevalent disease, especially in regions with primitive cultural techniques for barley production (El Yousfi and Ezzahiri, 2001). Barley is severely affected by net blotch, resulting in high average severity and yield losses ranging from 14% to 29% (El Yousfi and Ezzahiri, 2001; April et al., 2010). In addition, septoria diseases and leaf rust reach epidemic levels in certain regions, causing significant damage to barley crops (April et al., 2010). Hessian fly infestation also poses a threat to late-sown fields, further impacting yield (April et al., 2010). Meanwhile, Fusarium wilt remains a devastating disease in chickpeas, lacking effective management options (Amine et al., 2022).

Nematodes play a major role in soil improvement and ecosystem health, but their impact on wheat production worldwide is significant (Dababat and Fourie, 2018). The root-knot nematode (Meloidogyne artiellia) poses a significant threat to cereal crops, including wheat and barley, in the Mediterranean Basin (Dababat and Fourie, 2018). Moroccan wheat crops exhibit diverse characteristics of soil nematodes, which can serve as important indicators for soil biomonitoring on a large scale (Laasli et al., 2022). The presence of the root lesion nematode Pratylenchus spp. has been observed in various regions of Morocco, causing infestation percentages ranging from 5% to 34% (Mokrini et al., 2009). Controlling the root lesion nematodes through the cultivation of resistant varieties is an effective strategy for mitigating their impact on rainfed wheat fields (Mokrini et al., 2018). In conclusion, addressing foliar diseases, insect infestations, weed control, and nematode management are critical for improving crop productivity and sustainability in Moroccan agricultural systems. The use of resistant varieties, cautious interventions, and environmentally friendly control measures are essential components of integrated pest and disease management strategies (Ryan et al., 1998; Mrabet, 2011; El Fakhouri et al., 2021).

4.2.8 Weed control

Weed management is essential for improving cereal yields in Morocco, especially for wheat and barley. In Moroccan fields, weed densities can exceed 300 plants/m², significantly reducing crop yields if not properly controlled. Effective herbicide use has been shown to reduce weed densities, resulting in yield improvements of 15-20% in controlled trials (Zimdahl et al., 1992). Weed infestations can lead to substantial yield loss. For example, Boutahar (2000) reported that weed-free plots of bread wheat faced an 8% yield loss, while weedy plots experienced an 18% loss in the Chaouia region. Similarly, Tanji (2024) documented wheat grain yield losses ranging from 0% to 80% in both rainfed and irrigated trials, emphasizing the severity of weed impacts on production.

Recent studies in rainfed crop fields highlight additional challenges in managing broadleaf weeds, which are often resistant to common herbicides. These findings underline the importance of timely herbicide application and a combination of strategies such as crop rotation, mechanical weeding, and conservation agriculture to suppress weed growth while maintaining soil health (Tanji and El Brahli, 2018; Boutagayout et al., 2023). On-farm trials conducted in Chaouia between 2012 and 2015 showed the benefits of crop rotation and no-till systems for weed control. Diversified rotations, such as canola/durum wheat/durum wheat, reduced weed seedbank density by 68%, compared to only 23% in continuous durum wheat. Weed densities were also much lower in these diversified systems, highlighting the effectiveness of crop rotation in managing weed populations (Tanji et al., 2017).

Integrated Weed Management (IWM), which combines chemical, mechanical, and cultural strategies, is particularly effective in controlling weeds. However, further research and farmer training are necessary to tailor weed control strategies to Morocco's diverse agroecological zones for sustainable crop production (Boutagayout et al., 2023).

4.2.9 Institutional and government policies

The GMP and its successor, the Green Generation Strategy (2020-2030), have significantly shaped Morocco's agricultural sector, particularly in enhancing sustainability and productivity in cereal crops (Kmoch et al., 2022). These initiatives employ various strategies such as tree-planting, agricultural intensification, and the promotion of irrigation technology to achieve their objectives (Kmoch et al., 2022). Notably, the GMP places a strong emphasis on supporting solidarity-based agriculture to uplift small farmers, especially in disadvantaged regions (Hajar et al., 2020). A key feature of the GMP is its utilization of geographical indications to promote rural development and increase smallholder farmers' income by marketing locally produced food (Lambarraa et al., 2021). This strategy aligns with the plan's goal of enhancing economic performance in rural areas and has contributed to the overall objectives of the initiative (Lambarraa et al., 2021). The GMP has shown significant economic impacts, with an annual increase in agricultural GDP by 5.25% over ten years, creating substantial added value to the economy (Kdimy et al., 2022).

The GMP and the Green Generation Strategy have catalyzed comprehensive research efforts to assess the impact of agricultural practices and land use on production under climate stress (Amiri et al., 2021). Advanced technologies, such as machine learning and remote sensing, have been integrated into forecasting cereal yields, as demonstrated by studies like Bouras et al. (2020). These technological advancements offer valuable insights for policymakers in Morocco, aiding proactive decision-making and resource allocation to support cereal production. Furthermore, the GMP has stimulated extensive research on water management and irrigation practices, with studies investigating energy-efficient irrigation systems aiming to optimize water use in agriculture, thereby enhancing water security (Sokol et al., 2019).

Despite its strengths, several gaps persist within the policy framework of the GMP, particularly concerning implementation strategies for cereal production. These gaps include limited access to credit for small-scale farmers, bureaucratic complexities hindering subsidy distribution, and water management challenges threatening sustainable agricultural development (Asedrem, 2021). The shift from cereals to high-value crops as promoted by the GMP may have implications for agricultural productivity and food security. Changes in tillage practices and nitrogen fertilization during transitions between crop types can influence soil properties and crop yields, potentially leading to water stress and impacting overall productivity (Maher et al., 2023).

Building upon the successes of the GMP, the Generation Green Strategy aims to comprehensively address its shortcomings (ADA, 2012). This initiative emphasizes enhancing market access, improving post-harvest storage facilities, and implementing adaptive measures to mitigate climate change vulnerabilities affecting cereal production. By focusing on inclusivity and effectiveness, Generation Green seeks to ensure sustainable growth and resilience in cereal crop production throughout Morocco for the next decade (Ministry of Agriculture, 2021).

5 Conclusion

This review focused on understanding the key drivers of crop yields in Morocco from 1990 to 2024, examining 135 papers and prioritizing the study of cereals, particularly wheat, which holds significant importance in Moroccan agriculture. The analysis explored the impact of various climatic and non-climatic factors on crop yields. Extensive research was conducted on climatic variables such as precipitation, temperature, drought, CO2 levels, and other climatic events, alongside non-climatic drivers, including water management, soil conditions, irrigation techniques, and socio-economic factors. Unlike previous studies that often focus on individual crops or specific regions, this work integrates findings across various crop categories and agroecological zones, offering a comprehensive synthesis that highlights the complex interactions shaping agricultural productivity in Morocco.

The inclusion of recent references enhances the relevance of this study, addressing current agricultural challenges and gaps in the literature. By examining both environmental factors like precipitation and temperature alongside socio-economic drivers such as infrastructure, policy, and market dynamics, this work provides actionable insights into the multifaceted nature of crop yield determinants. The analysis also emphasizes the importance of national policies like the Green Morocco Plan and their role in shaping sustainable agricultural development. While existing studies offer valuable insights into different facets of cereal production, specific areas remain underexplored or require more detailed analysis to inform policy and practice effectively.

One significant research gap revolves around the impact of extreme weather events on cereal production in Morocco. Assessing the vulnerabilities of cereal crops to droughts, floods and other extreme weather phenomena, along with non-climatic factors, can aid in developing targeted strategies for enhancing climate resilience and adaptation in the agricultural sector. Further exploration is warranted into the determinants of cereal crop and seed commercialization among smallholder farmers in Morocco. Research in this domain can elucidate market dynamics, value chains, and barriers to commercializing cereal crops, ultimately enhancing farmers' income and market access. By considering a wide time span and incorporating both traditional and modern practices, this study underscores the potential of integrated, climate-smart agricultural strategies to enhance sustainability and resilience.

The potential for early forecasting of cereal yields using advanced technologies, such as AI and remote sensing, in different Moroccan regions is particularly promising. This approach offers opportunities to assist farmers, policymakers, and stakeholders in making informed decisions and managing production risks effectively. By bridging scientific knowledge and traditional practices, this study offers a framework for future research and actionable solutions.

Based on the findings of this review, prioritizing interventions in irrigated environments, adopting water conservation techniques, sustainable practices, and promoting legume-based rotations are recommended. In rainfed regions, incentivizing practices like no-tillage, increased phosphorus and nitrogen fertilizer usage, and adoption of certified seeds are also suggested. Implementing these approaches not only reduces reliance on chemical inputs but also enhances the overall sustainability of the agricultural system. Moreover, there is a need for a paradigm shift in agricultural policies, considering the complementarities and interactions between rainfed and irrigated systems. By fostering collaboration among agricultural departments, research institutions, and cultural bodies, this study offers a holistic perspective on Morocco's agricultural sector. The insights provided aim to address the challenges posed by climate change and socio-economic constraints while paving the way for achieving a prosperous "Green Generation." This comprehensive approach not only contributes to the scientific understanding of crop yield drivers in Morocco but also has significant implications for sustainable agricultural development in similar regions globally.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

SA: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. VO: Funding acquisition, Investigation, Supervision, Validation, Writing – original draft, Writing – review & editing. TE: Conceptualization, Methodology, Project administration, Resources, Validation, Writing – review & editing. DD: Conceptualization, Formal analysis, Supervision, Validation, Writing – review & editing. WS: Investigation, Validation, Visualization, Writing – review & editing. LO: Validation, Writing – review & editing. AC: Funding acquisition, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fagro.2025.1515938/full#supplementary-material

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