





Review

Towards Lower Greenhouse Gas Emissions Agriculture in North Africa through Climate-Smart Agriculture: A Systematic Review

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Abstract: North Africa (NA) is supposed to lower emissions in its agriculture to honor climate action commitments and to impulse sustainable development across Africa. Agriculture in North Africa has many assets and challenges that make it fit to use the tools of Climate-Smart Agriculture (CSA) for mitigation purposes. This study represents a first attempt to understand if CSA practices are sufficiently established in NA to contribute to reducing agriculture emissions. A PRISMA-inspired systematic review was carried out on an initial 147 studies retrieved from Scopus, Google Scholar, and the Web of Science databases, as well as from gray literature. 11 studies were included in the final analysis since they report the mitigation and co-benefits of CSA-based practices within NA. A bias risk was identified around the optimal inclusion of studies produced in French, and a specific plan was set for its minimization. Synthesis results revealed that most studies focused either on improving soil quality (nine studies) or managing enteric fermentation (two studies). The review revealed a poor establishment of the CSA framework in the region, especially in sequestering GHG emissions. A set of recommendations has been formulated to address the identified gaps from research orientations and organizational perspectives and empower the CSA as an ally for mitigation in north African agriculture.

Keywords: climate-smart agriculture; sequestration; GHG emissions; mitigation; low emission; North Africa

1. Introduction

Most scientific analysis is unanimous regarding the current climate change trends. At the current rate of greenhouse gas emissions into the atmosphere, our “carbon budget’s” capacity to limit global warming to 2 °C will be soon exhausted. In its 2021 report, the IPCC stated that human-induced climate change is unequivocal and that many changes in some environmental components are already irreversible for centuries [1]. According to the

same UN agency, the 1.5 °C and 2 °C global warming limits will be exceeded during the current century unless concrete actions are implemented now and in the very near future, namely, limiting current and future greenhouse gas (GHG) emissions [1].

Adopted at COP21, the Paris Agreement aims to limit global warming to below 2 °C by the end of the current century and establishes the general orientations to achieve that goal. Its 4th article states, “Parties shall aim to balance anthropogenic emissions (by sources) and anthropogenic removals by sinks of greenhouse gases by the second half of the 21st century” (Paris Agreement). Although this historic agreement did not provide clear indications about the position of agriculture and food value chains in the set goal, it did highlight important mitigation opportunities for this strategic sector.

The opportunities for climate change mitigation within the context of agriculture lie in the double role of this sector against climate change, an actor as well as a victim. Agriculture accounts for 20% of global GHG emissions [2], and at the same time, it provides various carbon sinks by implementing specific agricultural practices [3]. In 2019, Africa’s contribution to global emissions from agriculture was around 22%, with 2.3 Gt CO₂-eq emissions equally from pre-farm-gate and land-use emissions [2]. Similar to other regions, including Asia, Africa experienced an increase in emissions from agriculture during the period from 1990 to 2019 (Figure 1). This can be attributed to the continual advancements and improvements in agricultural systems observed in recent decades.

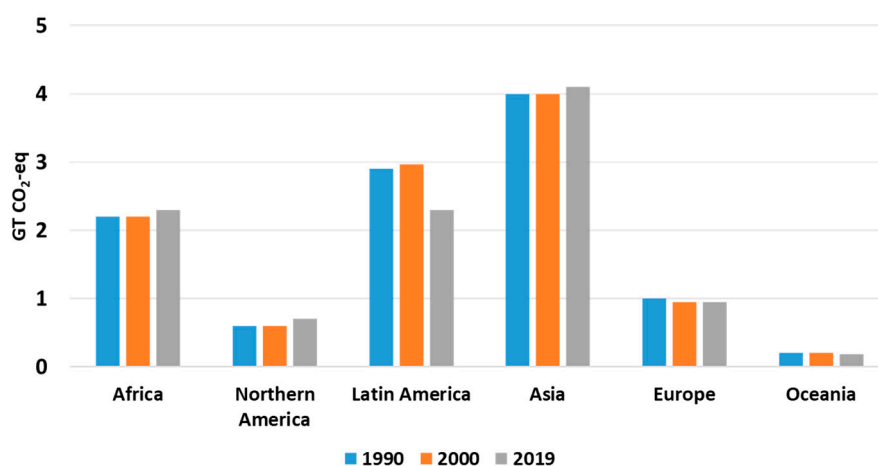


Figure 1. Trends in regional emissions from agriculture (1990, 2000, 2019) [2].

Within Africa, agriculture in the North Africa (NA) region has its specificities in terms of production system features and climate change challenges. With a Mediterranean climate in the north and the influence of the desert in the south, the region belongs to one of the global hotspots for climate change, with evident impacts on the agricultural sector [1]. Agriculture in NA is characterized by the dominance of wheat, barley, and olive trees in the Maghreb part, and mainly wheat, maize, and rice in the Nile delta and the Nile valley [4]. The share in total livestock units in NA is primarily comprised of chicken (23%), sheep (32%), and cattle (22%), in Morocco, Tunisia, and Algeria; chickens (22%), goats (16%), and sheep (46%), in Libya; and in Egypt, cattle and buffaloes make up 32% of the national livestock, while chickens represent 18% [5]. Agriculture holds significant socioeconomic importance in NA, similar to other African regions, providing substantial employment opportunities and contributing significantly to national GDPs, ranging from 11.4% to 14.2% [6]. However, unlike the rest of Africa, the agriculture sector in this region makes the smallest contribution (10%) to the overall GHG emissions from the food system, with enteric fermentation being the primary driver of these emissions [7].

Climate-Smart Agriculture (CSA) offers a promising framework to help achieve low-emission agriculture because it provides a framework to address food security and adaptation, but in a “sustainable” way. The concept of CSA was first presented by the FAO at the Hague Conference on Agriculture, Food Security, and Climate Change in 2010. The FAO’s

major ambition behind putting forward such an agricultural paradigm is to contribute to achieving sustainable development goals because CSA jointly integrates economic, social, and environmental dimensions [8]. CSA's three pillars are (i) improving incomes through the sustainable increase of agricultural productivity; (ii) building resilience and adapting the production systems; and (iii) sequestering (or reducing) greenhouse gas emissions. Rather than a set of actions, CSA is generally presented as a comprehensive and inclusive nexus of site-specific and challenge-driven practices to address food security and climate change in an integrated and systematic manner. The key components of the CSA concept include landscape, soil and water, genetic resources, livestock, fisheries and aquaculture, and energy, in addition to a consistent focus on finance and institutional aspects [8].

Theoretically, there are real opportunities for adopting CSA to tackle climate change impacts in NA due to the vulnerability of agriculture in this region to climate change and the expected decrease of its productivity under most future climate scenarios [1]. Furthermore, and on the same occasion, reducing GHG emissions from agriculture should bring high added value to this sector, which is considered "major" in most climate action plans of the countries in this region. However, this part of Africa is one of the regions with the lowest citations regarding CSA adoption (Thornton) as well as GHG mitigation efforts [9]. This observation represents one of the motivations behind the selection of this region in the present study, as barriers behind the poor adoption of CSA (including for mitigation) in NA deserve to be understood. Due to its strategic socioeconomic and geopolitical position within Africa, NA is supposed to impulse sustainable development within the continent, mainly through a clear dynamic around common topics such as climate change, food security, and the green economy. The authors believe that reviewing the obstacles burdening the optimal adoption of low-emission agriculture through the adoption of CSA in NA will contribute to empowering the role of this region in spurring sustainable development in Africa.

Some countries in NA, such as Egypt and Morocco, are global leaders in fresh and processed food commodity exports to Europe and the Americas; where regulations about the environmental footprints of goods are strict and are expected to become stricter in the near future as part of the mitigation commitments of these regions. This situation represents a concrete challenge for agricultural systems in NA, and awareness among authorities and the sector's actors seem low compared to the potential socioeconomic extent of these regulatory challenges on food exports from NA. On the other side, and to make the low emission transition viable across most of the economic sectors (including agriculture), emissions trading and carbon tax mechanisms are under development, which represent real opportunities for NA nations to fund their mitigation strategies and to shape out their sustainable development paths. Through the suggestion of low-emission agriculture in NA by adopting CSA, the authors aim to increase the awareness of the local actors in the agricultural value chain about both the potential challenges under the No-Action scenario as well as the opportunities lying behind the mitigation co-benefit of the CSA approach.

This paper seeks to understand the real position of the CSA framework within NA agriculture, with more focus on its mitigation perspective. We searched and analyzed publications covering the implementation of at least one of the CSA practices to address at least one of the mitigation aspects, with NA as the geographic scope of application. This allows reviewing the extent of CSA establishment in NA for lowering/sequestering in agriculture in this region.

The paper is divided into five sections. In the Section 2, a background of relevant literature is presented. In the Section 3, we introduce the adopted method to select and analyze the relevant publications. In the Section 4, the results are presented and in the Section 5 they are discussed, and in the Section 6, conclusions and recommendations are presented.

2. Background

Climate change mitigation opportunities in agriculture can be divided into three main groups of actions: (1) Avoiding or displacing emissions across the agricultural value

chain by avoiding direct GHG emissions from fossil energy and using bioenergy sources, for example; (2) Reducing emissions by managing Carbon and Nitrogen elements in an efficient way within the agricultural ecosystems; and (3) Enhancing removals through the building of Carbon sinks and their sequestration [10]. Concretely, a large amount of literature on mitigation technologies and practices in agriculture has been produced worldwide; their efficacy to reduce GHG emissions depends on several factors, but mainly on the local conditions [11]. Among the commonly recommended options are nutrient management [12], tillage management [13], residue management [13,14], agroforestry [15], crop rotation [16], bioenergy [17], improved livestock feeding technologies, genetic selection, Improved animal health and longevity, species shifts [18], and manure management [19]. One can notice that most of these practices, strategies, and technologies can form an ideal structure for a CSA framework since their (appropriate) establishment can promise, in addition to GHG mitigation, productivity increases as well as resilience to climate change impacts.

In Africa, the CSA concept has been endorsed since its introduction by many international and national organizations and communities; however, most of the literature reports the use of the productivity and adaptation pillars of CSA, with less emphasis on the mitigation dimension [20]. This is due to the productivity gap and the high food insecurity risk in Africa, which render adaptation to climate change and improvement of productivity the top priorities on the continent [21]. Despite being among the most vulnerable regions to climate change, Africa has a large potential for mitigation; this has been through various applications to showcase or check the efficacy of CSA in mitigation [9]. For example, Ambaw et al. [22] showed that the implementation of enhanced agroforestry practices in experimental sites in eastern Africa resulted in significant increases in soil organic carbon (SOC) stocks. These increases ranged from 42% to 185% (depending on the specific villages) in the top 15 cm of soil depth when compared to business-as-usual scenarios; Roobroeck et al. [23] claimed an improvement of SOC in the top 5 cm of the soil from 12.2 g C kg⁻¹ to 13.3 g C kg⁻¹ after several years of combining fertilizers and organic inputs in an experiment in a sub-Saharan site. Another experiment in Kenya reduced the GHG emissions intensity (from 2.4 to 1.6 kg CO₂-eq kg⁻¹ milk) by introducing large quantities of Napier grass in the forage [24].

From a research review perspective, several authors have reported on the extent of CSA adoption in Africa; most took either the adaptation or productivity dimension as a topic perspective and either sub-Saharan, eastern Africa, or southern Africa regions as a geographic scope perspective [25,26]. A similar observation was reported by Anuga et al. [21] when analyzing CSA potential in mitigation within Africa; this study was designed to provide a narrative and systematic review of articles on CSA in Africa with quantitative GHG emissions reduction. From the initial 228 articles, only 20 papers were selected for review. Four papers examined global or arid regions as the geographic extent, 16 addressed southern Africa, eastern Africa, and sub-Saharan Africa, and no paper covering NA (specifically) was selected or found. The authors used ten keywords about CSA mitigation and sustainable land management, searched many research engines (e.g., SCOPUS and Web of Science), and restricted the research to articles and reports edited exclusively in English. Widening the set of research keywords by using those most common in NA and languages other than English, especially reports and articles edited in French, a language widely used in the Maghreb region, might enable a broader capture of work on CSA options for mitigating GHG emissions in NA.

In this article, and by setting the reference status on tested climate-smart practices for mitigation efforts in NA, the review synthesis will be relevant for CSA-related literature in NA and will help in positioning this region in the continental and global maps of mitigation-centric CSA. Details about the key practices that have been tested and the methods used will help to understand the maturity of CSA in NA. At the same time, this article will contribute to showcasing the status of the low-emission transition because all countries in

this region have signed the Paris Agreement, and some are facing strict future restrictions in terms of the GHG emission footprints of their exports to Europe.

3. Materials and Methods

A systematic review approach was adopted to assess the added value of CSA to mitigate climate change in NA. In the systematic review approach, research works covering the initially formulated question are systematically and explicitly selected and appraised, and relevant data are analyzed from the research included in the review [27]. More specifically, the different searches, selections, and analysis steps in this paper were inspired by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach [28]. The key research question in our systematic search is: “Do CSA practices are sufficiently established in NA to contribute to reducing agriculture’s GHG emissions in this region?”. Answers to this question make it possible to guide researchers, operators, and decision makers in both CSA implementation and GHG emissions reduction in agriculture within this region. By “North Africa”, we mean Egypt, Libya, Tunisia, Algeria, and Morocco because they all align with most definitions of this ecoregion, and they are all equally covered in most climate change investigations as they are all part of the Mediterranean hotspot.

3.1. Search and Inclusion Process

The databases SCOPUS, Google Scholar, and Web of Science were used to run the search. Additional searches in the gray literature, mainly in English and French, were conducted to search for potential reports complying with the criteria set for this work. All reviewed articles with results on the contribution of climate-smart practices and technologies in reducing/removing/avoiding emissions in north African agriculture were targeted in the search. For optimal inclusiveness, we considered all works investigating (at least) one climate-smart practice (even if the CSA term was not explicitly mentioned and the CSA framework was not adopted properly), and quantitative finding(s) about (at least) one aspect of climate change mitigation within one country (or more) in the NA are addressed. A specific aggregate Boolean search string was developed and used as follows:

“Climate smart agriculture” OR “Climate smart” OR “improved livestock” OR “livestock management” OR “enteric fermentation” OR “manure management” OR “conservation agriculture” OR “conservation tillage*” OR “reduced tillage” OR “tillage intensity” OR “No till*” OR “water conservation” OR “sustainable irrigation” OR “agroforestry” OR “sustainable landscape management” OR “nutrient management” OR “residue management” OR “residue retention” OR “soil management” OR “sustainable intensification” OR “sustainable land use”)

AND

“mitigation*” OR “greenhouse gas emission” OR “emission reduction” OR “emission removal” OR “decarbonization*” OR “low emissions” OR “low carbon” OR “soil organic carbon” OR “SOC” OR “carbon sequestration*” OR “carbon capture” OR “carbon sink” OR “CO₂ sink” “carbon footprint” OR “GHG intensity” OR “life cycle assessment” OR “life cycle analysis” OR “enteric emissions”)

AND

“North* Africa*” OR “Morocco” OR “Tunisia” OR “Algeria” OR “Egypt” OR “Libya”).

The developed search string was applied to titles, abstracts, and keywords. For the search in French, the same Boolean search string was translated into French, and only reviewed documents were considered. To be included in the current review, articles needed to provide quantitative results about at least one aspect of GHG emissions reduction, removal, or sequestration through one or more climate-smart practices or technologies tested in the NA region. Even though CSA was only publicly introduced in 2010, due to the low number of research works complying with the previous condition, we considered articles published prior to the official presentation of the CSA concept as far as a climate-smart practice was tested and mitigation aspects in agriculture were addressed within the NA region.

In accordance with PRISMA guidelines regarding bias management during the systematic review process, the authors have identified a potential bias source in the search step, which is the risk of having various French translation options for a single technical English word. As a bias risk minimization action, the authors took into consideration all the possible translation options of keywords during the search.

3.2. Search Results

A total of 147 articles initially found through searches in the three databases (126) and gray literature (21) were screened by reading the titles and abstracts. Seventeen articles were excluded as they were duplicates, and 119 articles were not considered in this review because they addressed assumptions about or qualitative descriptions of the potential for CSA practices in climate change mitigation (Figure 2).

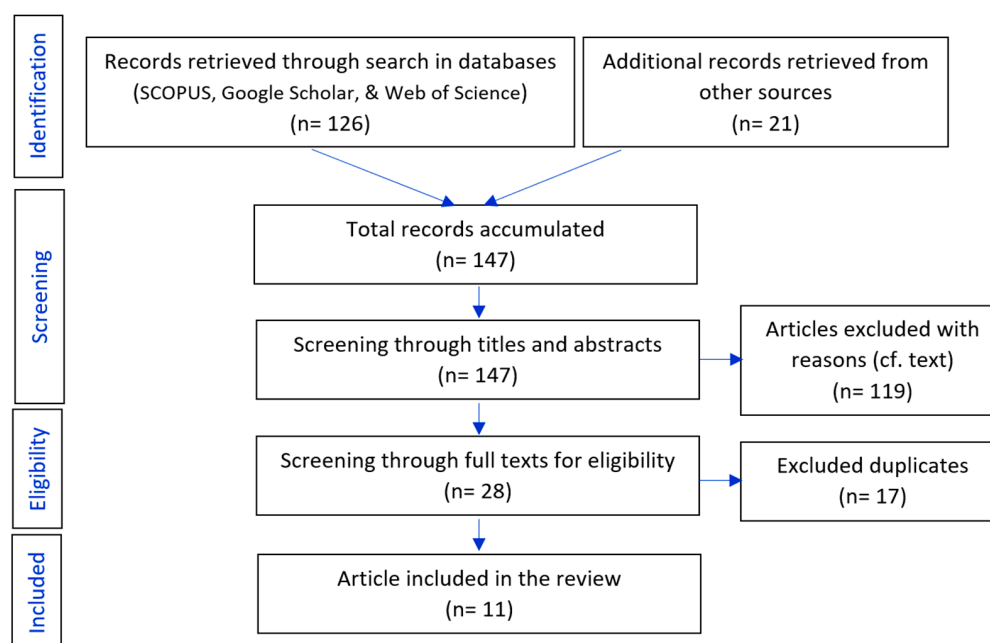


Figure 2. Search and inclusion process.

At the end of the search and exclusion processes, 11 studies were selected for review in this study. The included studies are represented (in Table 1) and sorted by the authors and year of publication, country of interest, evaluated climate-smart practice, used methods and approaches, and key findings.

Table 1. Details of the article included in the review.

Author(s), Year,	Country of Interest	Practice Evaluated	Methods, Approach	Key Findings
1. Bouazza et al. [29]	Algeria	alternative feedstuffs for ruminant nutrition	In vitro experiment	Leaves of <i>Atriplex halimus</i> and bark of <i>Calligonum azel</i> gave the lowest Methane production after fermentation (0.93 and 0.13 mmol g ⁻¹ dry matter, respectively) in comparison to other Algerian steppe browse species with Methane production ranging from 1.12 mmol g ⁻¹ dry matter to 2.63 mmol g ⁻¹ dry matter.
2. Mrabet et al. [30]	Morocco	conservation tillage system and crop rotation (separately)	Field experiment	No-Till system has increased the soil organic carbon (SOC) by 13.6% across 11-years of experiment; and the fallow-wheat-forage sequestered more SOC (increase of 11.7%), followed by fallow-wheat-lentils (11%) and continuous wheat (10.9%)

Table 1. Cont.

Author(s), Year,	Country of Interest	Practice Evaluated	Methods, Approach	Key Findings
3. Bessam and Mrabet [31]	Morocco	conservation tillage system	Field experiment	No-till system sequestered 3.5 t ha ⁻¹ and 3.4 t ha ⁻¹ of SOC more than conventional till system over 4 and 11 years experiments respectively
4. Ben Moussa-Machraoui et al. [32]	Tunisia	conservation tillage system	Field experiment	No-till system increases soil Carbon stock by an average of +4% to +7% compared to conventional till and depending on crop type after 4 years tests.
5. Attia et al. [33]	Egypt	Organic amendment, crop rotation, residue management, and conservation tillage system	Field experiment and modeling	Maize residue retention levels left (5 Mg ha ⁻¹) and 10 Mg ha ⁻¹ of compost increased total SOC by 6180 kg C ha ⁻¹ under no-till and maize-fallow rotation as average across 10 years. The same treatment but with no residue left gave 1101 kg C ha ⁻¹ increase of total SOC and gave 1535 kg C ha ⁻¹ in the treatment with 5 Mg ha ⁻¹ of residue and no compost applied (no till was applied to all treatments).
6. Lembaid et al. [34]	Morocco	Organic amendment, residue management, and conservation tillage system	Field experiment and modeling	+30% increase of SOC after adopting no-till practice over 9 years; and increase of SOC sequestration potential from 415 kg C ha ⁻¹ to 1787 kg C ha ⁻¹ under no-till practice, and from 150 kg C ha ⁻¹ to 818 kg C ha ⁻¹ (after 9 years) under conventional till system after increasing residue rate (to 90%) and applying 1 t ha ⁻¹ of manure
7. Moula et al. [35]	Algeria	Animal genetics enhancement	survey	High producing dairy cattle has lower emission intensity (24.1 kg CO ₂ -eq kg ⁻¹ milk and meat protein) than low producing cattle (50.9 kg CO ₂ -eq kg ⁻¹ milk and meat protein)
8. Ben Mbarek et al. [36]	Tunisia	Organic amendment and conservation tillage system (separately)	Field experiment	High soil organic matter (3.19%) in no till treatment for 80 years as well as in conventional till with annual application of 5l m ⁻¹ of olive mill wastewater for 20 years (1.78%) compared to conventional till treatment (0.82%)
9. Bahri et al. [37]	Tunisia	residue management, and conservation tillage system	Modeling	Projections revealed higher decrease in SOC under semi-arid condition for conventional till treatment (−76%) than for no-till (−70%) and no-till and residue retention (−46%) in 2075–2094 compared to 2016–2035. In sub-humid area, the gain in SOC accumulation is computed to be +102% for no till, +75% for conventional till, and +25% for no till with residue retention in 2075–2094 compared to 2016–2035
10. Ibno Namr and Mrabet [38]	Morocco	Crop rotation, residue management, and conservation tillage system	Field experiment	After 4 years experiment, the highest SOC found in No-till with 50% of surface covered by residue (18 g kg ⁻¹) and in no-till with 100% surface covered by residue (17.7 g kg ⁻¹) compared to conventional till (14.3 g kg ⁻¹) in the 0–2.5 cm depth; no significant difference in higher depths. SOC was not significantly affected by crop rotation with slight advantage for continuous wheat at deep depth; SOC was not significantly affected by residue level under no-till at all the three depths due to retardation in crop residue degradation
11. Fenni, Nadjem, and Mekhlouf [39]	Algeria	residue management and conservation tillage system	Field experiment	260 g C m ⁻² and 257 g C m ⁻² of sequestered carbon in no-till and residue retention over durum and bread wheat crops respectively. 50% to 70% less fuel observed in no-till wheat cropping system compared to conventional till treatment.

4. Results

4.1. Broad Outlook on the Studies

Of the 11 studies selected, one was implemented in Egypt, three in Algeria, three in Tunisia, and four in Morocco; no studies were retrieved about Libya. In terms of tem-

poral distribution, three studies were conducted between 2000 and 2009 (studies 2, 3, 10), four studies between 2010 and 2019 (studies 4, 7, 9, 11), and four during 2020 and 2021 (studies 1, 5, 6, 8). The research teams behind the studies included in this review might have researchers representing centers from other regions than NA, but all the first authors are affiliated with North African organizations. In terms of the agricultural value chains of interest in the studies, nine studies focused on the crop production aspects, and only two covered the livestock branch (studies 1 and 7). None of the eleven studies, despite testing one (or more) sustainable practices, explicitly mentioned CSA; productivity was the major research motivation. To address the different mitigation aspects, researchers in the included studies used mostly field experiments alone or combined with other approaches (eight studies in total); the other approaches included in vitro laboratory investigation, modeling, and survey.

4.2. Key Findings of Studies

Within the studies focused on crop production, the most tested agricultural practice is the conservation tillage system (41% frequency) (Figure 3), alone or combined with one or more practices. Soil organic carbon (SOC) and soil organic matter (SOM) are the most-adopted indicators to assess the efficacy of the tested practice. In the two studies where only the no-till technique was tested, the authors reported that this practice is providing a significant increase in SOC, mainly in the top layer of soil, compared to conventional tillage treatments, and the differences start to become more significant over various seasons of no-till application. Examples include a +7% increase in SOC after 4 years in study 4, +289% after more than 80 years in study 8 [32,36], and up to a +25% increase after 4 years and +13.6% in study 2 after 11 years [30,31]. In study 11, Fenni et al. [39] proved that a no-till practice could save from 50% to 70% fuel compared to conventional till treatment, in addition to the increase in SOC. Combining the no-till strategy with other techniques also gave a positive increase in SOC, such as in study 10, which found SOC was increased by +25.8% by implementing no-till and residue retention (covering 50% of the surface) [38]. The same combination (study 9) allowed a smaller decrease of SOC potential in the Tunisian semi-arid region by the end of the current century (−46% in no-till and residue retention treatment vs. −76% in conventional till treatment) [37].

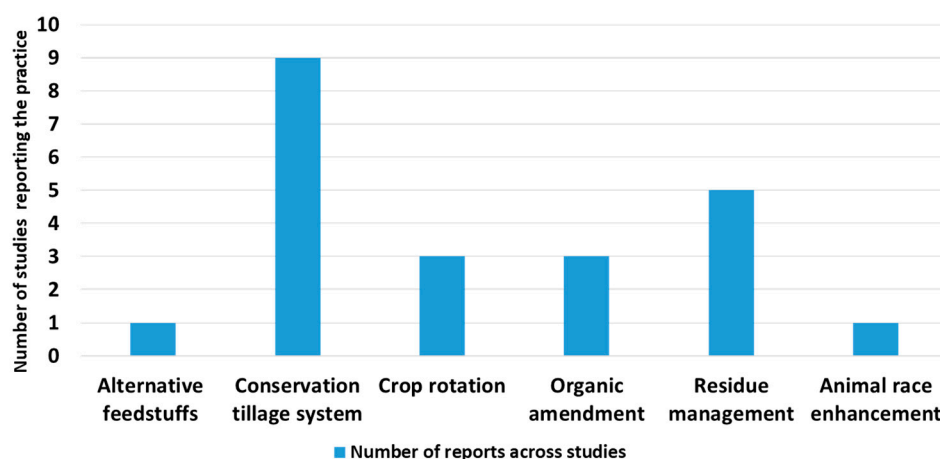


Figure 3. Total number of reports of each climate-smart practice across the included studies.

Techniques other than no-till practice were successful in increasing SOC, such as residue retention and application of 1 t ha^{-1} of manure, which helped to improve SOC by +445% after 9 years of application in study 6 [34], and the rotation practice that made it possible to secure an increase of +11% to +11.7% in SOC depending on the rotation scheme in study 2 [30]. In study 10, no significant difference was found between crop rotation, no-till combined with residue retention at deep soil depths, and the conventional treatment [38]. Bahri et al. [37], in study 9, computed the low performance of no-till

combined with residue retention against conventional till in terms of SOC accumulation in the sub-humid area in Tunisia by 2075–2094 compared to 2016–2035.

The approaches differed in the two studies covering the livestock branch (studies 1 and 7). Bouazza et al. [29] addressed enteric fermentation through an in-vitro fermentation experiment of a set of steppe species and found that two species (*Atriplex halimus* and *Calligonum azel*) have low methane production compared to the other tested steppe species; the methane reduction rate can go to -95% in the case of the bark of *Calligonum azel* [29]. In study 7, and through the analysis of survey results, Moula et al. [35] used the emission intensity indicator to prove that high-production cattle in Algeria are promising from a greenhouse gas management perspective. In Algeria, high-production cattle dominate in terms of average annual numbers and cumulative emissions compared to low-production cattle. According to the authors calculation, the low emission intensity of high-production cattle ($24.1 \text{ kg CO}_2\text{-eq kg}^{-1} \text{ protein}$) compared to low-production cattle ($50.9 \text{ kg CO}_2\text{-eq kg}^{-1} \text{ protein}$) gives them potential for both food security and climate change mitigation plans.

5. Discussion

5.1. Research Orientations and Findings

Interest in soil capacity for sequestering and storing carbon has increased within the scientific community, and many authors have proved the importance of SOC in climate change mitigation strategies in addition to its role in resilience and yield increase [40–42]. Therefore, monitoring SOC stocks in most of the studies included in this review aligns with international scientific efforts and takes legitimacy from the quality of soils in the NA region. According to Darwish et al. [43], soils in NA are C-deficient with SOC levels below the threshold of 30 tons ha^{-1} ; this can be explained by the dominating climate (arid-semi-arid), the sparse natural vegetation, and the adoption of unsustainable growing practices in some situations (e.g., excessive irrigation). The other justification for the focus on soil quality and especially on their content in organic carbon is the importance of climate change impacts in this region. NA is part of a climate change hotspot where extreme events are already more frequent and will continue on that trend under most projections [1]; such conditions are responsible for carbon dioxide emission and carbon capture reduction by soils [44].

In terms of results diversity, most of the authors in the considered studies reported the positive impact of the tested practices on SOC levels in the shallow layers of soil, albeit to different extents. The difference in extents is generally caused by the variability in the pedo-climatic conditions of the experiments and some differences in the protocol, such as the number of years of monitoring. The soil-crop-climate combination can introduce variability in the efficacy of the tested cropping practice [45]. Overall, the positive correlation between years of adoption of sustainable practices (such as no-till, rotation, and residue retention) and the increase in SOC stocks in shallow soil depths was proved in many other areas with similar conditions, such as in Spain [46]. Among the potential explanations are that the accumulation of residues generally happens at the soil surface, and in some soil types, oxygen levels are low in subsoil layers, which limits the movement of organic C downward [47].

Animal husbandry is very important in the NA region from a socioeconomic perspective and is generally practiced within agro-pastoral systems. Livestock is a major contributor to global GHG emissions at 14% alone, and cattle have the highest emission factor compared to other species [48]. Although estimates of GHG emissions from livestock are influenced by various factors, including species, numbers, types, and region-specific emission factors [49], the dominance of sheep in the composition of national herds in NA would be one of the contributing factors to its comparatively lower emissions compared to other ecoregions characterized by a high ratio of cattle. Livestock's role in reducing GHG emissions in agriculture is widely agreed upon, and most global CSA research agendas are focusing on two aspects: enteric emissions and manure management. The two included research works cover enteric emissions and suggest two practices to address GHG emissions: improving feed and improving production efficiency through high-production breeds. Much literature has proved

the efficacy of similar measures to limit livestock's contribution to GHG emissions [50,51], and most specialists report that more efforts are needed in this branch [52].

5.2. Maturity of Low-Carbon Agriculture in NA

By limiting the search to the potential of climate-smart cropping techniques to lower GHG emissions in agriculture, this review's synthesis helped in understanding the status of research on the mitigation of pre-farm-gate emissions. At this stage of the agricultural value chain, most research efforts are split between refining calculations of the emission factors, seeking solutions to reduce the emissions, and enhancing the sequestration potential [53]. The analysis of the included studies that focus on the crop system branch reveals that GHG mitigation is still not a high priority with the NA research community (at least in the pre-farm-gate stage). This assertion is founded on the limited number of retrieved studies, the excessive importance of productivity and resilience aspects in all studies, and the weak correlation of the findings with GHG mitigation perspectives. Knowing the importance of agriculture in NA as well as the GHG mitigation ambitions of some individual countries in NA, it becomes clearer that further research in low-carbon agriculture is needed.

All the considered countries in NA have submitted their NDCs except Libya. Tunisia, Algeria, and Morocco have set targets for conditional GHG reduction by 2030 of 45%, 22%, and 45.5%, respectively, with agriculture as a major driver of mitigation within the non-energy sectors [54]. Egypt has not provided figures about the targeted reduction but has confirmed the role of the agriculture (and water) sector in its plan to reduce GHG mitigation [55].

In some countries, the agricultural sector contributes significantly to the national trade balance by exporting fresh produce and processed food. The values of agricultural merchandise exports were around USD 5.6 billion for Egypt in 2020, USD 1.7 billion for Tunisia, and USD 7.7 billion for Morocco in 2019 [56]. All three countries have ambitious plans to empower their export-led agriculture to drive their respective national development; however, these ambitions might be confronted with some market regulatory challenges, especially in Europe, the principal buyer of NA's agricultural exports. In its efforts to achieve climate neutrality by 2050 (EU Green Deal), the European Union has put in place a series of sustainability strategies for strategic sectors, such as the "Farm to Fork Strategy" for agriculture and food systems and the Biodiversity Strategy for the protection of natural resources. Reducing and labeling the environmental and carbon footprint of agricultural products (both locally produced and imported) are some of the key measures in most related proposals. The status of mitigation in agriculture in NA that has been assessed by this review suggests that more effort will be needed.

5.3. Status of Mitigation-Focused CSA

In the previous section, efforts toward pre-farm-gate mitigation in NA were found to be weak. Because no explicit mention of the CSA concept was reported in the covered studies, the adoption of the CSA paradigm for mitigation in NA can be considered an illusion, at least from a research perspective. This confirms the findings of [25,57] as in both reviews about studies on CSA adoption aspects, the NA (and the Middle East) regions were the least represented. For proper implementation of CSA, it is necessary to look at the synergies and trade-offs between its three pillars of food security, adaptation, and mitigation. With the current yield gap in the NA region in most of the strategic crops and the effects of climate change that have begun to be obvious in many aspects of the food system, the priority of the actors in the NA agricultural value chain is increasing productivity and resilience. Among the few explicit tentative approaches to CSA in the NA region, Brouziyne et al. [58] designed and simulated a CSA framework to grow rainfed wheat and sunflowers in the north-western part of Morocco under current and projected conditions, but the focus of the author was productivity increase and resilience building. The other potential constraint behind the low adherence to CSA (in general) in NA is that progress is strongly reliant on the collective adherence of many stakeholders, such as research and

development organizations, policy makers, and farmers. From this perspective, several initiatives have been launched to increase awareness about the importance and outcomes of CSA in NA; most are led by the FAO. However, CSA adoption in NA countries is facing various challenges related to the poor advocacy of this framework, the lack of organizational and institutional settings to enable the environment (including markets and extension services), as well as low capabilities and poor access to technologies.

In Europe, and particularly in the southern part where many cropping systems and agroecological zones are in common with NA, many authors have highlighted the low pace of adherence to CSA, but the reasons and their extent might be uneven from country to country. Various economic barriers were studied, such as the hidden costs of CSA implementation, poor access to capital, and long pay-back periods [59–61], and a set of behavioral bottlenecks were identified by other authors, such as conflict with conventional farming practices, farmers level of education, and the lack of management awareness [59,62]. As per the institutional and organizational levels, it is mainly the lack of regulatory framework and institutional support, as well as poor access to information and technologies, that were confirmed as barriers hindering CSA implementation in Europe in many studies [24–64].

Similar to our findings in this study, most of the aforementioned investigations of the CSA in Europe reiterated that although the CSA should be considered the integration of the three pillars, it was not always the case in the literature, where the authors found that the focus may be on a single pillar or a combination of only two, mainly the productivity and resilience pillars.

6. Conclusions and Recommendations

This review work has identified studies conducted on the contribution of climate-smart practices and solutions to GHG reduction in agriculture in NA and has analyzed their findings to develop a characterization of the status of CSA and mitigation efforts. The review has also highlighted a set of gaps to be addressed to empower low-carbon farming through CSA in NA.

The studies included have either focused on increasing SOC through some cropping systems (for the studies on the crop system branch) or tackling enteric fermentation by putting forward the importance of alternative feed or breed selection for the livestock-focused studies. These studies reported promising results that join the findings of similar investigations in other regions. Due to the vulnerability of most soils in NA, further research is still needed using other climate-smart practices such as intercropping, grasslands management, and agroforestry, with more emphasis on the quantification of GHG sequestered and avoided by practice or solution. Similarly, the livestock sector in NA is important and evolving dynamically to address food security in the area; more research on enteric fermentation and manure management is important to use this sector in the local plans for GHG mitigation.

In vitro testing of different low-GHG emissions practices and technologies can be an important preliminary intervention prior to any in vivo experiment. This promising technique has the advantage of being short-term and cost-effective and can be combined with modeling to expand the tested variants of practices and technologies. However, the in vitro technique needs to be adopted with caution as it may be misleading in some situations (e.g., the feature of return to normal after an intervention of the rumen).

The system approach is also needed in the design of efforts to lower GHG emissions in NA in order to capture all trade-offs and co-benefits that might reside across the agricultural and food systems. For example, research on reducing enteric fermentation by exploring alternative forages can also investigate the balance between the emissions and resource footprint across the growing phase and the effect on animal productivity. Integration between different systems is also required due to the interlinkages between them, such as the connection between ecosystems, agricultural systems, and water systems. Further research is needed in this regard since all studies confirm that successful adaptation and mitigation efforts need to be systemic for a better and more durable impact. The low num-

ber of studies retrieved by this systematic review suggests a low interest in pre-farm-gate mitigation within the research base for such a region with high ambitions on GHG emissions and unavoidable international trade restrictions in relation to the carbon footprint. Adopting a proper CSA framework is expected to help foster the low-carbon transition in the agriculture of NA. Proper CSA is possible only through inclusive integration of climate change mitigation in the planning of resilient and high-productivity agricultural strategies, and research has a wide range of opportunities to contribute to that perspective. The CSA approach is a site-specific and challenges-centric agricultural paradigm; research on climate-smart frameworks, techniques, and solutions regarding NA's agricultural challenges needs to consider the potential and the opportunities of sequestering and reducing (or removing) GHG emissions. In addition to the researchers, further efforts from other stakeholders, including governmental institutions and development organizations, are needed to establish a favorable ecosystem for CSA establishment in NA. Since more attempts have been made to analyze CSA in southern parts of Africa, Asia, and Europe, further investigations might be carried out to understand the CSA history and ecosystems in these areas from socioeconomic, organizational, and institutional perspectives, as well as from behavioral perspectives, to identify learnings and upscaling opportunities towards more developed CSA (with a significant mitigation aspect) in NA.

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