agriculture

Systematic Review

# Agronomic Strategies for Sustainable Cotton Production: A Systematic Literature Review

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**Abstract:** Cotton, with a cultivated area of $31.92 \times 10^6$ $ha^{-1}$ across 80 countries and an estimated annual turnover of USD 5.68 billion, is the world's leading natural textile fiber. However, many cotton-producing countries have neglected to improve production practices, adversely affecting the environment and society. A systematic review of the sustainable cotton cultivation literature was performed for the first time to identify and suggest context-specific agricultural strategies that can be applied within different agroecosystems. The key aspects include (1) inoculation with arbuscular mycorrhizal species such as *Gigaspora margarita*, *Funneliformis mosseae*, and *Acaulospora scrobiculata* to enhance root exploration, biomass, and nutrient uptake; (2) using grass, legume, and brassica cover crops as a valid alternative to monoculture and fallow crop rotations to reduce resource depletion and increase the sustainability of cotton production; (3) adopting drip and mulched drip irrigation systems over traditional furrow and sprinkler systems for water conservation; (4) exploring the feasibility of prematurely terminating irrigation in humid subtropical and Mediterranean climates as an alternative to chemical defoliation without affecting cotton yield. This paper, which describes various farming practices adopted in different climates, provides farmers a guide for eco-friendly cotton agronomic management without sacrificing productivity.

**Keywords:** sustainable cotton; agronomic strategies; crop rotation; mycorrhizal species; water conservation

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## 1. Introduction

Cotton (*Gossypium* spp.) is the world's most important natural textile fiber, which is grown in ~80 subtropical and tropical countries [1]; due to the wide global distribution of the crop, it is advisable to be cautious about its sustainability. The concept of sustainability itself has undergone various definitions over the years, and the most widely used and accepted one is that proposed by the United States (USA) Environmental Protection Agency, which states that the use of resources for present needs should not compromise the ability of future generations to meet their own needs [2]. According to the latest data provided by the USA Department of Agriculture [3], herbicides have been used in 96% of cotton-growing areas in the USA. In particular, glyphosate isopropylamine salt is used on 45% of these acres, glyphosate potassium salt is used on 38%, paraquat on 27%, the dicamba diglycolamine salt on 25%, and diuron on 22%. Other chemicals are used in 68% of these areas. Insecticides are "only" used on 39% of these areas [3]. The reasons behind the lower use of insecticides can be attributed to the widespread use of genetically modified

(GM) varieties, such as Bt (*Bacillus thuringiensis*) cotton, which were designed to control cotton bollworm (*Helicoverpa armigera*) [4]. However, the massive use of Bt cotton has resulted in strong resistance to the two families of Bt toxin (Cry1A and Cry2A) all over the world, as highlighted in China (Cry1A) [5,6], India (Cry1A and Cry2A) [7,8], South Africa (Cry1A) [9,10], Argentina (Cry1A) [11], and the United States (Cry2Ab) [12].

Additionally, broad-spectrum herbicides such as glyphosate doubled on cotton in the USA territory from 2010 to 2019, according to the data reported by the USDA National Agricultural Statistics Service [3]. The phenomena of weed resistance [13], growth inhibition of some soil bacterial species [14], and the risks to the environment and humans [15] are just some of the reasons for moving towards eco-friendly alternatives. Another factor that should be considered is the nutritional requirements of cotton. According to the USDA, in the 2021 growing season, farmers applied nitrogen to 71% of the growing areas at an average rate of 100 kg $ha^{-1}$, for a total of $3.15 \times 10^6$ Mg. This was accompanied by phosphate, potassium, and sulfur, which had a total contribution of 0.11, 0.13, and $0.02 \times 10^6$ Mg, respectively [3]. Nevertheless, the extensive use of mineral fertilizers has strong environmental impacts, particularly on soil microorganisms and organic matter turnover, which are key factors for soil fertility [16]. Some nutrients, such as phosphorous (P), which is considered a non-renewable resource, are decreasing globally, resulting in a rise in prices over the recent years [17]. Moreover, most P fertilizers are immobile in soils since they are strongly adsorbed to iron and aluminum cations at low soil pHs and calcium under alkaline conditions [18]. A possible solution to this issue may be offered by soil microorganisms such as arbuscular mycorrhizal fungi (AMF), which play an important role in maximizing nutrient uptake due to their ability to effectively explore a higher soil volume, increasing the plant's nutrient uptake, mainly of P [19].

Cotton is a summer crop that leaves the soil bare during winter. Indeed, a notable concern in cotton production is the limited quantity of crop residues remaining on the soil surface after harvest compared to other crops [20]. This deficiency has implications for the content of soil organic matter [21] and for cotton productivity [22].

Another aspect covered in this review article is water use. Agriculture is the world's largest user in terms of consumption and water withdrawal. Recent estimates show that the global crop consumptive use stands at 8053.6 $km^3$ $year^{-1}$, accounting for 87% of the global water consumption [23]. Cotton is an irrigated crop but it requires modest water inputs compared to other crops with similar growing cycles. Currently, the most widely used irrigation system in cotton cultivation is furrow irrigation [24–26], which has low efficiency and significantly increases waste.

There is abundant scientific literature on the sustainable agronomic practices of cotton cultivation concerning fertilization, weed control, and proper water resource management. However, to the best of our knowledge, a comprehensive review that encompasses all these aspects is still lacking. For this reason, in this review, we analyzed, for the first time, the studies on sustainable cotton cultivation from different production areas around the world in order to disseminate information and guide farmers toward environmentally friendly management. In particular, we focused on the role of microorganisms in reducing the agronomic inputs and increasing soil fertility, as well as the adoption of conservation practices such as crop rotation and cover cropping to restore the soil's natural balance. Furthermore, the review identifies the most recent agronomic strategies and tactics for water reduction, irrigation systems, and irrigation termination.

## 2. Materials and Methods

This systematic review was conducted following the PRISMA guidelines [27]. The first step was the collection of a corpus of articles related to the research topic by using relevant keywords such as "sustainable cotton cultivation" or synonyms ("responsible", "ethical", and "green"), "cotton water-saving irrigation strategies" or synonyms ("innovative", "modern", "latest", and "emerging"), and "arbuscular mycorrhizal fungi on cotton" or synonyms ("AMF species", "root-associated mycorrhizae", and "mycorrhizal symbionts"). These keywords were selected as they were deemed the most representative of the research objectives. To achieve a high scientific impact for this review, the previous keywords were searched on three databases (Scopus, Web of Science, and Science Direct), and the following inclusion criteria were adopted:

- Peer-reviewed articles written in English were included;
- Conference papers, conference reviews, and book chapters were not reviewed;
- The most recent and informative papers from the same experimental topic were given priority.

In the second step, the articles were screened by reading their abstracts to identify those that addressed the research question. Articles that were not related to the topic, despite being identified by the search query, were discarded. The articles that reported quantitative data on the use of sustainable practices in cotton cultivation were selected, while those that did not quantify the effects of the case studies or had insufficient or unrepresentative data were not considered. Among the studies published up to August 2024 (the date of the last search), the 119 searches across the three databases returned a total of 1262 results. Of these, 187 duplicates were removed from the dataset and 708 were excluded due to irrelevant content. The full texts of the remaining 367 articles were then reviewed and 77 eligible articles were included in the qualitative summary. Full details of the screening process can be found in the PRISMA flowchart in Figure 1. In addition, the PRISMA checklist was included in the Supplementary Materials.

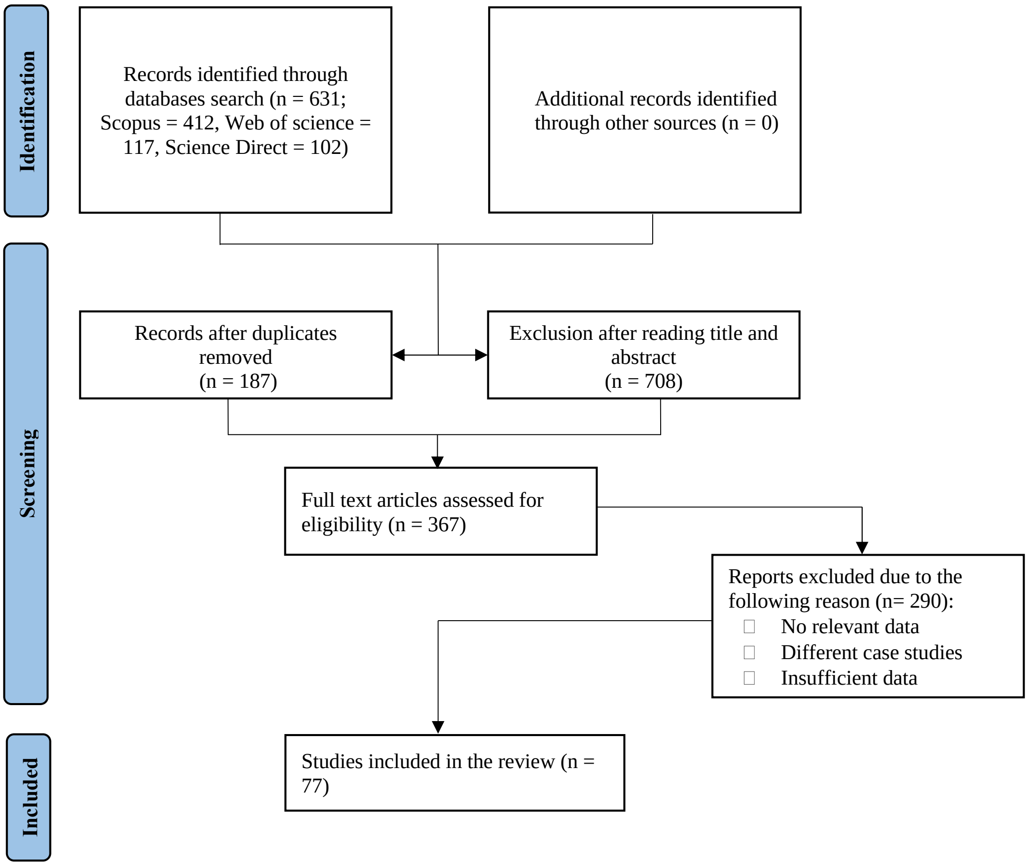


**Figure 1.** Flowchart of the results of the literature search.

## 3. Results and Discussion

This section presents the results of the literature review on sustainable cotton cultivation around the world. Within it, various topics falling under the theme of sustainability are addressed. Starting with plant–microorganism relationships, through to the use of polycultural systems and reducing water inputs. Finally, the last section is reserved for final remarks based on the results of the review.

### 3.1. Cotton Production and Literature Database

The latest estimates from 2020 indicate that the global cotton production stands at $24.2 \times 10^6$ t, which had more than doubled compared to earlier data from the 1960s. Moreover, with a production of 6 million tonnes, China is the world's largest producer, followed by India and the United States (Figure 2a,b) [28].

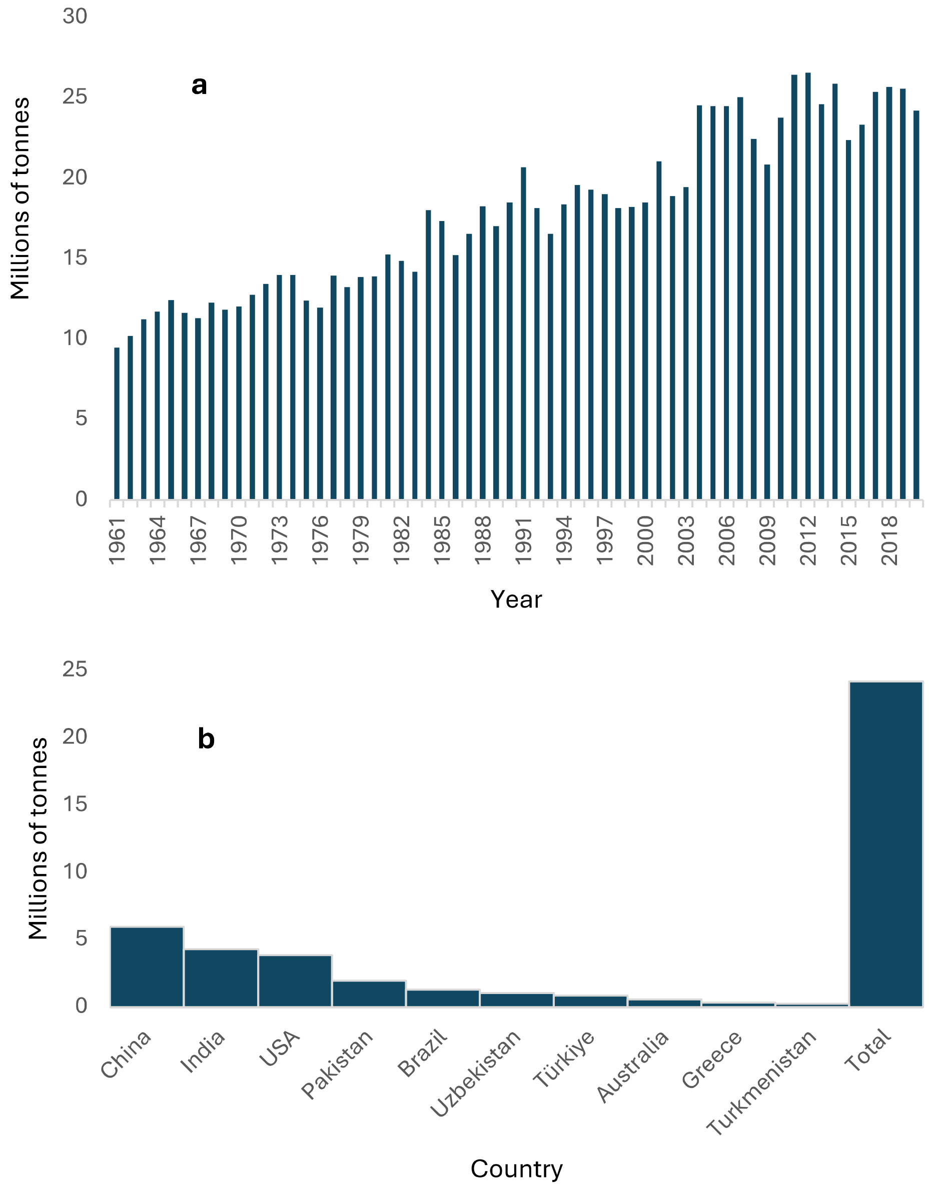


**Figure 2.** World cotton production: (**a**) production of ginned cotton lint around the world (1961–2021); (**b**) top 10 producers of cotton lint (average for 1961–2021) [28].

Similarly, scientific research on sustainable cotton production has also seen a notable expansion in recent decades, from the first article published in 1981 to 22,800 in 2022, for a total of 111,000 document results, when using the keyword "sustainable cotton" within the Scopus® database (Figure 3).

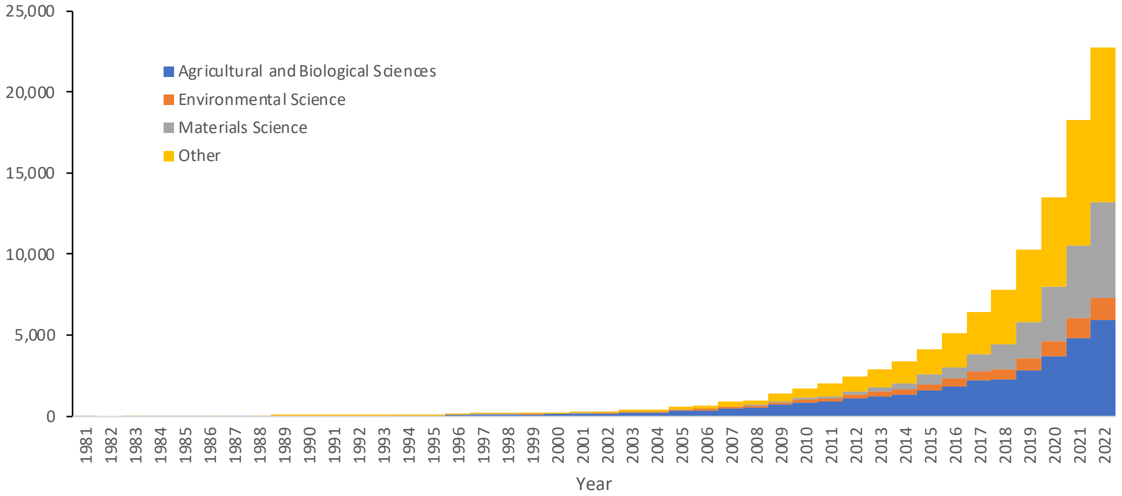


**Figure 3.** Global scientific publications on "sustainable cotton", 1981–2023, on Scopus®.

The publication of articles on cotton cultivation significantly increased after the 2010s in terms of annual number of articles, countries, and institutes publishing on sustainable cotton topics. Furthermore, the areas of research, indicated in Figure 3 as "other", have also increased, which represents the numerical difference between the total number of articles and those present in the subject areas of "Agricultural and Biological Sciences", "Environmental Science", and "Materials Science" within the Scopus® database. This is emblematic of the fact that over the years, sustainable cotton cultivation has gained the interest of other scientific areas, not just purely agronomic fields.

### *3.2. Mineral Nutrients and Plant–Microorganism Relationships*

The large use of mineral fertilizers has a serious impact on the environment and soil [29], and their long-term practice has contributed to reductions in the soil organic matter content [30], increased soil acidification [31], and environmental pollution [32]. Therefore, the challenge for modern agriculture is to switch to sustainable fertilization practices and find alternatives to increase the amount of available nutrients for plants.

In this scenario, plant–microorganism relationships, which occur at the level of the rhizosphere, are of key importance to improving plant growth and the product quality of field crops [33–36]. It is known that some microorganisms, such as AMF, can establish symbiotic relationships with cotton [37,38], thus improving the crop in terms of vigor, nutrient uptake (especially P and Zn) ability [39], flowering, and boll maturation [37]. Up to 90% of the length of cotton roots can be colonized by AMF [39], which provides a significant benefit to the plant. The extra-root hyphae of AMF [40] help the root system in exploring a larger soil surface [41] and increasing the plant's nutrient uptake, mainly of P [42]. In particular, the growth range of cotton hyphae can extend up to 30 mm from the root surface when P fertilizers are not applied [19]. In some cases, this can result in an increased P absorption range of up to 15-fold. However, greater colonization of the root system does not always mean a better plant nutritional status [43]. In article [44], it was reported that plant P uptake is not necessarily related to the percentage of root length colonized by mycorrhizae; on the contrary, they observed that with increasing soil P supply, the mycorrhiza-inducible P transporter genes were down-regulated, resulting in a decreasing proportion of colonized root length.

In accordance with the findings of [35], the authors of [45] observed that the Apparent Phosphorus Recovery (APR) significantly decreased with increased application rate (150–300 kg $P_2O_5$ $ha^{-1}$), demonstrating how a low P application rate (75 kg $P_2O_5$ $ha^{-1}$) not only increased root length and hyphal density but also improved the spatial distribution of cotton roots in the soil, thus increasing the APR. In contrast, other studies [38] reported no significant change in the percentage of root length colonized in response to P fertilizer application in cotton plants.

P is not the only soil nutrient whose cotton plant uptake may undergo changes with AMF application. Mycorrhizae hyphae can contribute to between 60 and 85% of Zn uptake depending on the AMF species [46,47]. It is well known that Zn is an essential micronutrient for normal healthy growth and the reproduction of cotton, playing a key role as a regulatory cofactor for a wide range of different enzymes [42,48]. However, there is an antagonistic relationship between P and Zn. Since high P fertilizer applications suppress mycorrhizae inoculation, plants cannot obtain more Zn [39]. This dynamic changes if there is a high Zn application. The authors of [42] observed that a high Zn application (10 mg Zn $kg^{-1}$ soil) to sterilized soils deficient in P (0 mg $P_2O_5$ $kg^{-1}$ soil intake) significantly reduced the uptake of P (−31%) in cotton plants mycorrhized by *Funneliformis mosseae*. In contrast, Zn application (10 mg Zn $kg^{-1}$ soil) significantly increased P uptake (+48%) in mycorrhized cotton plants grown in sterilized soil with sufficient P (100 mg $P_2O_5$ $kg^{-1}$ soil intake). Over the last few years, the research has focused on identifying the AMF species capable of bringing the greatest benefits to cotton, especially for P acquisition. Table 1 shows the selected AMF species and their advantages to cotton, highlighting their potential applications beyond the different range of minerals that each analyzed AMF species provides.

**Table 1.** Comparison and analysis of the main arbuscular mycorrhizal fungi (AMF) species used on cotton.

| AMF Species | Benefits | Target Parameter | Effect Compared to Uninoculated Control | Reference |
|---|---|---|---|---|
| *Acaulospora scrobiculata* | Nutrient uptake, increase in the surface area explored by roots and shoots | Root dry matter | +75% | [47] |
| | | P uptake | +59% | |
| *Claroideoglomus etunicatum* | Nutrient uptake, increase in the surface area explored by roots and shoots | Root dry matter | +56% | [47] |
| | | P uptake | +76% | |
| *Funneliformis mosseae* | Zn and P uptake (less than *C. etunicatum*) | P uptake | +110% | [42] |
| | | Effect on the soil microbiome | Higher abundance of Actinobacteria and Gemmatimonadetes | [37] |
| *Gigaspora margarita* | Nutrient uptake, increase in the surface area explored by roots and shoots | Ca, Zn, P uptake | +68% Ca, +69% Zn, +76% P | [38] |
| | | Effect on the soil microbiome | Higher abundance of Proteobacteria, Cyanobacteria, and Fusobacteria | [37] |
| *Glomus intraradices*, *G. viscosum*, and *G. mosseae* | Growth response of cotton nutrient uptake | N, P, K, Ca, Mn, Fe, Cu, Zn uptake | +65% N, +148% P, +92% K, +65% Ca, +129% Mn, +73% Fe, +91% Cu, +85% Zn | [45] |
| *Rhizophagus clarus* | Increase in P and nitrogen content in inoculated plants, root colonization | Effect on plant biomass | +81% | [47] |
| | | Shoot N uptake | +75% in N uptake | [47] |

In fact, the best strategy lies in the careful combination of different species, with the goal of promoting microbial interactions that fully meet the needs of cotton while reducing agronomic inputs and encouraging the adoption of sustainable agronomic tactics. For instance, the authors of [47] reported how the AMF species *Acaulospora scrobiculata* could produce significantly high values in root dry matter (+75% compared to uninoculated control), but at the same time, was less efficient in P uptake capacity (+59% compared to control). On the other hand, the species *Claroideoglomus etunicatum* showed lower values in root dry matter (+56% compared to the non-inoculated control) but a high P absorption capacity of 1 mg kg$^{-1}$, 76% higher compared to the non-inoculated control (0.57 mg kg$^{-1}$) [47]. In article [39], the authors reported even higher P values in soil treated with an inoculum of *C. etunicatum*, with an 80% increase in P (0.18 mg kg$^{-1}$) compared to the untreated control (0.1 mg kg$^{-1}$). Beyond *C. etunicatum*, the authors of [39] observed that the species *F. mosseae* was able to stock up P to 0.21 mg kg$^{-1}$, equal to 110% of that contributed by the untreated control (0.10 mg kg$^{-1}$) and 9% more than the species C. etunicatum (0.18 mg kg$^{-1}$ soil). *C. etunicatum*, on the other hand, performed better in Zn recovery (20.9 mg kg$^{-1}$ soil) than the untreated control (14.8 mg kg$^{-1}$ soil) and *F. mosseae* (20.1 mg kg$^{-1}$ soil). Furthermore, *F. mossae* has been shown to influence the taxonomic abundance of soil microbial populations. It was observed that an inoculum of *F. mosseae* resulted in a greater presence of Actinobacteria and Gemmatimonadetes, but at the same time, the soil contained Proteobacteria, Bacteroidetes, Acidobacteria, and Planctomycetes [40]. It appears that *G. margarita* also influenced soil microbial communities by promoting the colonization of Proteobacteria, Cyanobacteria, and Fusobacteria [40].

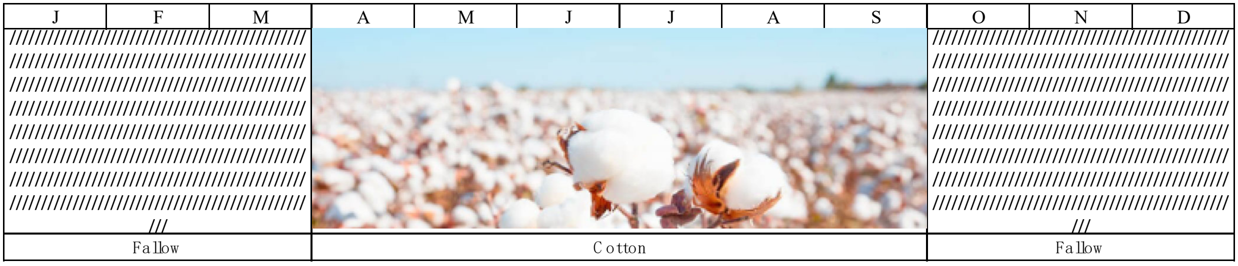
In recent years, some authors have observed how different AMF species can supply other essential nutrients to sustain cotton production in addition to the aforementioned P and Zn. For example, the authors of [47] noted that by inoculating soil with *Gigaspora margarita*, there was an increase of 68% in Ca, as well as a greater absorption of P (+76%) and Zn (+69%) compared to non-inoculated plants.

The authors of [49] found that an inoculum of *Rhizophagus clarus* was able to provide, in addition to a greater cotton biomass (+81%), a higher N shoot uptake (14 mg plant$^{-1}$) in comparison to the uninoculated control (7 mg plant$^{-1}$). In fact, in [46], a mixture of *Glomus intraradices*, *G. viscosum*, and *G. mosseae* was found to have a better contribution to the cotton plants' mineral uptake in terms of N (65%), K (92%), Ca (65%), Mn (129%), Fe (73%), Cu (91%), as well as of P (148%) and Zn (85%).

### 3.3. Monoculture and Polyculture Systems

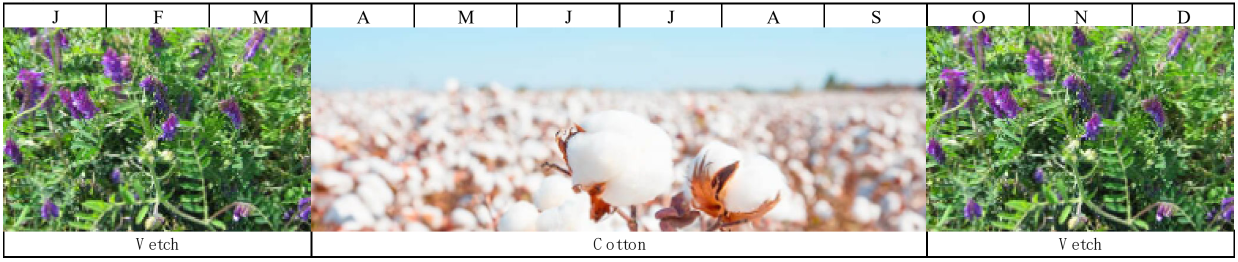
Cotton is a crop that requires large auxiliary inputs and leaves a very low content of biomass residues on the soil after harvesting, compared to corn, wheat, and soybean [20]. The lack of plant residues on the soil surface, especially under a monocropping regime [50], can explain the different environmental issues, including soil compaction and erosion [50], N gas emissions into the atmosphere [51], loss of nutrients [21], and decrease in cotton yields [22] (Figure 4a).

**Mono-Succession Cotton Cultivation System**



**a**

**Legume–Cotton Rotation System**



**b**

**Figure 4.** *Cont.*

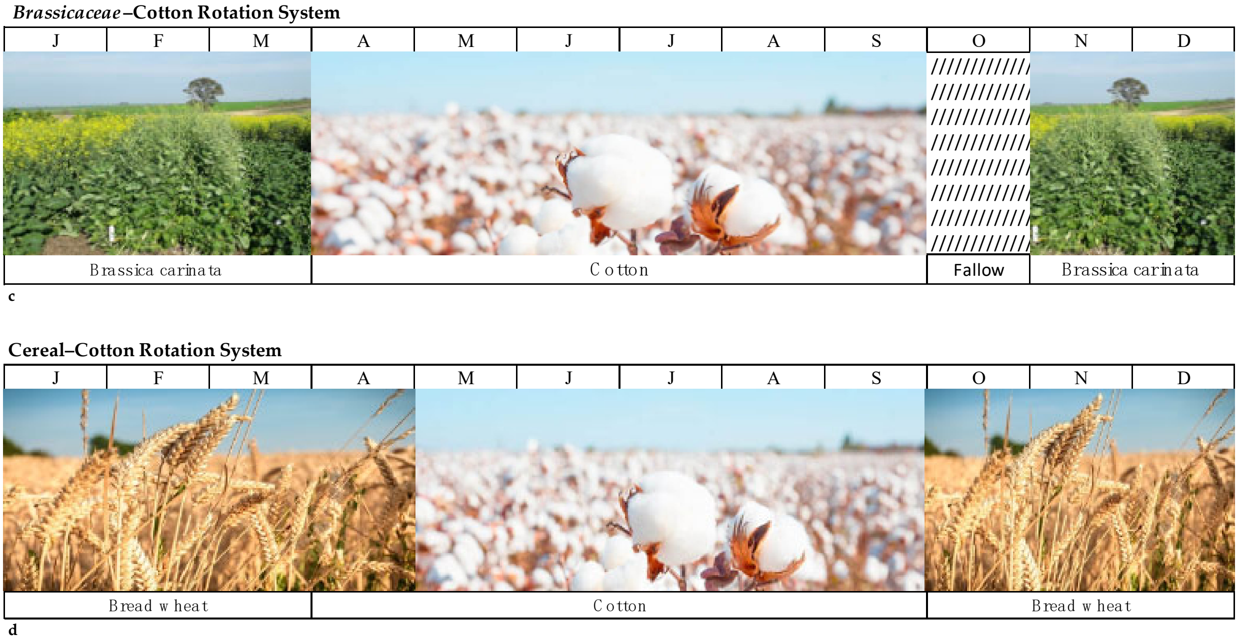


**Figure 4.** Possible crop rotation schedules for cotton cultivation. Letters indicate the months of the year: (**a**) Mono–Succession cotton cultivation system. Soil erosion, loss of nutrients, and reduced cotton yield are some of the phenomena related to the use of cotton in monoculture; (**b**) Legume–Cotton Rotation System. *Vicia villosa*—cotton rotation proposed by Li et al. (2021) [52] showed that vetch is useful for increasing soil total N concentration and making it more available to cotton, potentially reducing the need for nutritional inputs during cotton cultivation.; (**c**) *Brassicaceae*–Cotton rotation system. Tiwari et al. (2021) [53] observed that the use of *Brassicaceae*, specifically *Brassica carinata*, has an inhibitory effect on the growth of weeds, reducing competition during the early growth stages of cotton.; (**d**) Cereal–Cotton rotation system. Adeli et al. (2021) [21] proposed a cultivation system based on the *Poaceae*–cotton succession. *Triticum aestivum* residue after harvest, due to its high biomass quality, is able to significantly reduce the loss of nitrate N concentrations by leaching compared to conventional winter fallow.

Soil conservation polyculture systems, in particular cover cropping (CC), can assist in reducing soil erosion [54], enhancing the soil water content, stimulating beneficial soil microbial communities [40,55], controlling weeds [56–59], and reducing the use of herbicides, particularly in the early weeks after sowing [59]. Recently, several authors have focused on cereals, legumes, and brassicas and their mixes as a cover crop option to enhance both weed and nutritional management of crops.

### 3.3.1. Legumes

Legume cover crops can provide significant benefits, including an improved soil structure and reduced N losses by preventing runoff and leaching during the off-season [60]. For instance, in [36], the authors evaluated the rotational effects of winter and summer legumes grown before cotton to increase both the crop nutritional intake and soil structure. The experiments were conducted in Narrabri (NSW, Australia) on moderately fertile soil. On the one hand, the cultivation of grain-manured legumes was evaluated using *Vicia faba* L. and *Glycine max* L., which fixed 453 and 488 kg N ha$^{-1}$ in the soil, respectively. It was evaluated how green-manured legumes, using *Pisum sativum* and *Lablab purpureus*, were able to fix up to 209 and 240 kg N ha$^{-1}$, respectively, before the crops were mowed. These results evidenced how both strategies markedly influenced N fertilization rates, with a reduction of 99% for grain-manured and 244% for green-manured legumes, compared to cotton in a non-legume-based cropping system. The authors of [52] evaluated the influence of another green-manured legume, *V. villosa*, in a field trial conducted at the West Tennessee Research and Education Center in Jackson (Jackson, TN, USA) on silt loam soil with 0–2%

slopes. The vetch cover crop increased the soil total N concentration by 18% and microbial rate transformation rate by 168% compared to the untreated control. Moreover, it also enhanced soil labile N concentrations by 21, 79, and 57% for nitrate, ammonium, and extractable organic N, respectively. These results prove that *V. villosa*, in addition to fixing N, could keep it available to the plant, reducing the dose of N fertilizer needed (Figure 4b). The authors of [61] evaluated the benefits of intercropping cotton with mung bean (*Vigna radiata* L.) in an arid region of northwest China. The results showed that the legume intercropping system significantly increased the total soil N content (27.9–45.3%), total yield (16.6–19.8%), and water use efficiency (WUE) compared to the monoculture system.

However, there are also some drawbacks to using green-manured legumes. In fact, legume cover crops do not have a good persistence on the soil surface due to their low biomass production and low C/N ratio [62], thus limiting their effectiveness as a soil conservation tactic. Therefore, it is necessary to assess other plant species in combination with legumes to mitigate this weakness.

### 3.3.2. Brassicas

Planting *Brassicaceae* cover crops before cotton sowing can be a valid practice to reduce the summer weed seedbanks and support crop establishment. In a study in Florida (USA) on sandy loam soil, the authors [53] found that after planting *Brassica carinata*, the number of *Amaranthus hybridus* (−27%) and *Senna obtusifolia* (−25%) plants decreased. This suggests that cotton can benefit from less competition with weeds during its early stages of growth when preceded by *B. carinata* (Figure 4c).

In [63], a study conducted in Henan Province (China) on sandy loam soil, the authors found that intercropping cotton with *Orychophragmus violaceus* increased the soil organic matter (SOM) content by 15.6% and 36.7% at 0–20 and 20–40 cm soil depths, respectively, compared to a cotton–fallow cropping system. Additionally, the use of *Brassicaceae* increased the total N content and available N by 2% and 13.1% compared to the cotton–fallow system, respectively. In fact, although legumes are able to fix atmospheric N, they have a lower capacity to be incorporated into the soil than brassicas [63,64]. This can have a direct impact on cotton production in terms of an increase in the boll number $m^{-2}$ (+5.6%), grain yield (+10.3%), and lint yield (+12.6%) compared to the cotton–fallow system. It is important to underline the ability of *Brassicaceae* to produce glucosinolates, secondary metabolites of N- and S-containing anions whose hydrolysis by myrosinase gives a number of compounds, including isothiocyanate, nitrile, and thiocyanate [65], which have allelopathic activities on weeds, and their use could strongly reduce weed competition for cotton [66]. Moreover, glucosinolates are also harmful to herbivorous insects, such as the cotton bollworm (*Helicoverpa armigera*), one of the main pests of cotton. The authors of [52] evaluated the impact of glucosinolates on the growth and development of cotton bollworm larvae and observed that the survival rate of *H. armigera* pupae fed with 4 ppm glucosinolate was decreased to 32% compared to the control, whose pupae survival rate was 56%. Furthermore, the development duration of *H. armigera* larvae increased (+25.0%) when they were fed 160 ppm glucosinolate compared to the control. These findings suggest that the use of *Brassicaceae* cover crops may have potential for pest control in cotton crops.

However, the results obtained by the authors of [67] in Headland (AL, USA) regarding the use of Brassica plants in cotton cultivation are controversial. A radish (*Raphanus sativus* L.) cover crop before cotton sowing showed a smaller increase in the soil organic carbon (SOC) content compared to using different combinations of cover crops in the region's humid subtropical climate. The radish monoculture cover crop treatments resulted in SOC values of 6.57 g $kg^{-1}$ soil in the top 5 cm of soil, while the rye–clover–radish, rye–radish, and clover–radish cover crop combinations showed increases in the SOC content of 13, 8.5, and 7.7%, respectively.

### 3.3.3. Cereals

The use of cereal cover crops in cotton cultivation is well documented. The authors of [68] carried out a 40-year field experiment in a continuous cotton system to evaluate the use of two cover crop treatments (*Vicia villosa*, *Triticum aestivum*) compared to a control treatment as a conservation management approach to improve the SOC content in subsoil layers. The trials were conducted on well-drained clay soils in Jackson (TN, USA) under a temperate climate. Unexpectedly, the use of *T. aestivum* was found to be the most suitable crop in terms of SOC stock of 33.7 Mg ha$^{-1}$ at a depth of 0–60 cm compared to *V. villosa* at 29.1 Mg ha$^{-1}$ and the untreated control at 24.4 Mg ha$^{-1}$. Specifically, *T. aestivum* resulted in a 23% and 34% higher SOC content than *V. villosa* and the control, respectively, at depths of 10–30 cm and 30–60 cm.

The authors of [69] argued that this is due to the low C/N ratio in *Brassicaceae* and *Fabaceae*, making these crops prone to mineralization processes and making them sources of available nutrients in the short term, especially nitrogen. Conversely, *Poaceae*, due to their high lignin content and soil persistence, improve physical characteristics and increase the ion exchange capacity [70]. The authors of [71] showed that cotton rotated with soybeans (twice in a 4-year period) reduced the cotton lint yields (1.12 Mg ha$^{-1}$) more than the continuous cotton crop system (1.20 Mg ha$^{-1}$), while cotton rotated (twice in 4 years) with corn (1.22 Mg ha$^{-1}$) did not show any appreciable differences in lint yields compared to continuous cotton cultivation. This contrasts with the results obtained in [22], where it was demonstrated that including soybeans twice within a 4-year rotation decreased the cotton yield by 16% more than the continuous cotton monoculture over the entire study period and including corn (once in a 4-year period) also decreased the cotton yields compared to the untreated control (2.7 and 3.1 Mg ha$^{-1}$, respectively).

The field study conducted in [72] in eastern Arkansas (USA) investigated the effects of cereal rye (*Secale cereale* L.) cover crops and no cover crops over several years on the properties of the soil used in cotton production. Soil samples were collected from raised beds (B), wheel track (WT), and no wheel track (NWT) furrows. The results highlighted that the SOM content in the WT furrows under cereal rye cover crops was 30.7 Mg ha$^{-1}$, higher than all the other treatments and position combinations. In addition, the water stable aggregate concentrations were 1.6 times higher in the WT furrows under cover crops compared to no cover crops.

*Poaceae*–cotton rotation also has the advantage of reducing nitrate leaching. The authors of [21] conducted a two-year study in Mississippi (USA) and reported that the presence of bread wheat during the rainy season and their residual presence after harvest can reduce nitrate N concentrations in leachate samples by 45% and 21% (9.9 and 17.2 mg L$^{-1}$) compared to winter fallow (18.2 and 22 mg L$^{-1}$) in the first and second year, respectively (Figure 4d).

### *3.4. Water Management*

Cotton can be grown under rainfed conditions only in a limited number of cropping environments, and usually, an optimal production level cannot be achieved without irrigation [73]. Therefore, appropriate water resources management is essential for cotton production to achieve a high quantitative and qualitative performance for fiber and grain [74,75]. The water requirements for cotton differ around the world and depend on the local climate, soil characteristics, genotypes, growing season duration, and irrigation management [76].

Several studies around the world [77–80] showed that the cotton water requirement varies from 700 to 1200 mm during the growing season, which depends mainly on the growing area [76,81,82].

Studies have shown that the values are comparable to each other. In [81], the authors, using the Parlier lysimeters in the San Joaquin Valley, California (USA), reported crop evapotranspiration (ETc) values of 710 and 845 mm in 1998 and 1999, respectively. Likewise, the authors of [83] in California (USA), using a water balance model, reported that the water use ranged from 594 to 778 mm depending on the irrigation method. In Syria, the authors of [79] measured cotton evapotranspiration using a water balance model and found an average seasonal ETc of cotton equal to 878 mm over a 3-year period. But, as expected, the highest ETc values were found under arid and semi-arid climatic conditions. For instance, in 1998 and 1999, in the semiarid regions of Lapaz, Yuma, and Mohave (AZ, USA), the authors of [81] reported cotton mean seasonal ETc values of 1362, 1035, and 1034 mm, respectively. Consequently, cotton requires a significant water supply during the cropping season to ensure satisfactory productivity and product quality results. For this reason, in recent years, researchers from all over the world have turned their attention towards irrigation management strategies capable of both satisfying crop water requirements, preserving such a precious natural resource, and reducing the economic impact of this practice.

### 3.4.1. Irrigation Systems

A study [73] conducted in southeastern Anatolia (Turkey) showed that cotton yields were significantly higher when using drip irrigation (DI) (4380 kg ha$^{-1}$) compared to furrow irrigation systems (FI) (3630 kg ha$^{-1}$) and sprinkler irrigation (SI) (3380 kg ha$^{-1}$). In addition, the averaged values over 4 years indicated that DI produced 30% more grain than SI and 21% more than FI. These data were also confirmed by the WUE, with values of 4.87, 3.87, and 3.36 kg ha$^{-1}$ mm$^{-1}$, respectively, for the DI, FI, and SI methods [73]. In Uzbekistan, the authors of [84] observed that, over three seasons, by combining DI with programmed irrigation set at three levels (germination, squaring, and boll maturation, respectively, at 70–70–60% of the field capacity [FC]), it was possible to increase the water use efficiency (WUE) by 71% on average compared to that of FI. This was also a determinant for grain cotton production, which increased by 14% compared to FI. Furthermore, using DI at 70% of the FC resulted in a 32% irrigation water savings compared to FI when following the same scheduling rule. In article [85], the authors also demonstrated that subsurface DI in cotton can reduce the off-site movement of pesticides and improve the WUE compared to FI. In southeastern Anatolia (Turkey), the authors of [86] compared DI and low-energy precision application (LEPA) systems and subjected these to different levels of ETm restitution to achieve cotton-production goals. The results revealed that the LEPA system, thanks to the precise control of irrigation applications, was able to achieve very high seed cotton yields (4750 kg ha$^{-1}$, with consumption of 854 mm of water), reaching the average values of DI (5040 kg ha$^{-1}$ with a seasonal irrigation volume of 868 mm). Conversely, the studies conducted in [87] in Texas, USA, reported higher water use in LEPA systems compared to subsurface drip irrigation (SSD), thereby questioning their usefulness. In fact, it was observed that from cotton sowing to day 195, the SSD system was able to use 20 to 30 mm ha$^{-1}$ of water less due to the lower evaporation losses. Such a volume of water produced 25 to 50 kg ha$^{-1}$ of additional cotton lint yield in semi-arid environments [88].

In the districts of Maharashtra (India), one study [89] showed significant success in the adoption of DI. In fact, 91.1% of the cotton cultivated area was using DI, while only 8.9% was irrigated with non-micro or conventional sources. The authors pointed out that the adoption of DI resulted in an 80% increase in cotton yield. Furthermore, after the implementation of this technique, the use of electricity for irrigation per hectare was reduced by 86%, with clear economic benefits.

The use of DI also seems to be useful from a nutritional point of view. The authors of [90] in 2016–2017 in Urumqi (China), under arid climatic conditions, observed how DI also had an impact on nutrient uptake compared to flood irrigation (FLI). Surprisingly, the P concentrations were higher in DI than FLI in most cotton organs, demonstrating that the irrigation method positively affected nutrient uptake. In fact, the P uptake in the shoot of plants was significantly higher under DI (157.6 mg plant$^{-1}$) compared to FLI (140.6 mg plant$^{-1}$). Similarly, higher percentages of P were found in other plant organs under DI (1.02% in reproductive organs and 0.71% in leaves) compared to FLI (0.85% in reproductive organs and 0.64% in leaves). Furthermore, the shoot biomass (stems and leaves) under DI (18.7 g plant$^{-1}$) was significantly higher than that under FLI

(15.6 g plant$^{-1}$). Despite the evident effectiveness of drip irrigation, in many areas of the world, it remains the least employed system for cotton crops [91]. A study indicated that approximately 80% of the Australian cotton growing area is irrigated using gravity surface-irrigation systems, and only 3% of cotton is irrigated with subsurface drip-irrigation systems [25]. The same is true in the United States, although there are significant differences depending on the geographical area. LEPA sprinkler irrigation dominates much of the southern High Plains and actually represents over 75% of the irrigated area in the region [26]. However, in the Midsouth, favored by deep alluvial soils, high annual precipitation, and long, frost-free cropping seasons, irrigation is predominantly accomplished through FI (70 to 80%) and center pivot methods [24,26].

Despite the positive qualitative and productive results, DI presents some gaps in cotton cultivation that must be addressed. As reported in [92], DI also has limitations, particularly during the germination phase, since it does not ensure uniform soil moisture during the early phases of cotton growth. According to the authors, SI systems are more efficient during this critical phase. Another study conducted in Georgia (USA) [93] revealed that between overhead SI, DI, and rainfed conditions, there were no significant differences in terms of lint yield, indicating that all of these methods did not affect fiber quality. Additionally, unlike SI systems, subsurface DI can cause the accumulation of salts above the depth of the drip line, as it does not result in leaching [92].

In the arid region of Xinjiang (China), the authors of [94] carried out a study on the use of mulched drip irrigation (MDI), which is achieved by combining drip irrigation and mulching with plastic film. The results highlighted that, compared to traditional FLI, the soil moisture content at a depth of 0–60 cm under MDI increased by 4.8–12.9% from the full flowering stage to the boll open stage, promoting the growth and development of fine roots at the full flowering stage and prophase full boll stage [95] and an increase in the root/shoot ratio [94]. The authors of [96], in Xinjiang (China), a region with a typical arid continental climate, evaluated the environmental impact of MDI, in addition to its impacts on biomass and lint yield. While MDI significantly improved the biomass (61.5%) and yield of cotton (12.8%) compared to the non-mulched control, there was an increase in $CO_2$ emissions. Over two cotton-growing years, the total $CO_2$ emission increased both when MDI was applied in narrow rows (25.3%) and wide rows (28.9%) compared to the control.

The study conducted in [97] explored the impact of MDI on the stability of soil aggregates in cotton fields in northwestern China, focusing on how different durations of MDI (0, 9, 13, 15 and 23 years) affected the SOC content and salinity levels. The results indicated that as the MDI duration increased, the aggregate-associated SOC concentration in all fractions increased significantly, while the salt concentration decreased significantly. Specifically, the total SOC content increased by 0%, 11%, 17%, and 87% after 9, 13, 15, and 23 years of MDI, respectively, while the total salt content decreased by 33%, 68%, 67%, and 76% over the same periods.

While MDI offers several benefits, it is important to also consider some potential drawbacks. Recent studies from six cotton fields in Xinjiang, China, where MDI had been practiced for 5 to 19 years, reported an accumulation of residual plastic film (RPF) ranging from 121.8 to 352.4 kg ha$^{-1}$, with an annual increase of 15.7 kg ha$^{-1}$, predominantly at a depth of 0–30 cm [98].

Regarding $CO_2$ emissions, the authors of [99] investigated the correlation between the presence of RPF from drip irrigation mulch in the soil and the release of greenhouse gases in Xinjiang, China. Surprisingly, they found a negative correlation, where increasing amounts of RPF were associated with decreasing $CO_2$ emissions. This phenomenon can be attributed to the fact that RPF can interfere with soil moisture content [100], reduce the ability of crops to absorb water and nutrients from the rhizosphere [101], impair soil microbial activity [101], and lead to a decline in crop yield and quality [102]. These factors likely inhibited cotton root development, leading to reduced plant biomass accumulation and diminishing the carbon sequestration potential of cotton fields [99].

Table 2 illustrates how scientific research has directed its focus toward the choice of irrigation method in relation to the climatic area. It is possible to observe that in arid environments, researchers have focused on using DI to maximize the efficiency of water resources as much as possible [90]. In semi-arid areas, attention was given to the use of mulching as a support for DI [94,96]. Due to the better water availability in milder climatic areas, such as the Mediterranean basin, there was a greater interest in SI [73,92].

**Table 2.** Geographical distribution of scientific research regarding cotton irrigation systems. DI: drip irrigation; LEPA: low-energy precision application; MDI: mulched drip irrigation; SSD: subsurface drip irrigation. Numbers in bold represent the total number of articles for each climatic condition.

| **Irrigation System** | **Effects** | **Climate** | | | | **Location** | **Reference** |
|---|---|---|---|---|---|---|---|
| | | **Arid** | **Arid Continental** | **Mediterranean** | **Semi-Arid** | | |
| **DI** | | **2** | **1** | **2** | | | |
| | Less efficient in the germination phase compared to SI | | | 1 | | Şanlıurfa, Turkey | [92] |
| | +14% seed-cotton production compared to FI | | 1 | | | Uzbekistan | [84] |
| | +19.8% shoot biomass compared to FLI | 1 | | | | Urumqi, China | [90] |
| | +20% cotton yield compared to FI and +29% than SI<br>+25% WUE compared to FI and +35% compared to SI<br>+30% seed-cotton production compared to FI and +21% compared to SI | | | 1 | | Anatolia, Turkey | [73] |
| | +12.10% shoot P content vs. FLI | 1 | | | | Urumqi, China | [90] |
| LEPA | | 1 | | | | | |
| | −5.75% seed cotton yields compared to DI<br>+1.61% D3 water consumption compared to DI | 1 | | | | Southeastern Anatolia, Turkey | [86] |
| MDI | | | | | 2 | | |
| | +61.49% biomass production compared to DI | | | | 1 | Xinjiang, China | [96] |
| | +12.84% cotton yield vs. DI<br>+4.80%–12.87% soil moisture content (from full flowering to the bolls open stage) vs. DI | | | | 1 | Xinjiang, China | [94] |
| SSD | | | | | 1 | | |
| | Irrigation water saving compared to LEPA | | | | 1 | Texas, United States | [87] |

### 3.4.2. Irrigation Termination Strategies

Under organic cotton farming systems, the main challenge is harvest management. A lack of green leaf material is essential at this stage, as it reduces the moisture content, leaf trash, and other impurities and improves the fiber grade [103]. However, there are no sustainable alternatives for defoliating cotton plants without compromising production. Besides thermal defoliation, the only option is to interrupt irrigation to promote cotton defoliation [104–106]. Several researchers have raised questions on the correct time to perform this critical practice and how it may impact cotton production and quality. Based on the data obtained in [107] regarding the irrigation termination (IT) on FI systems, the authors of [108] observed that, in the humid subtropical climate of Mississippi (USA), interrupting irrigation from 5 to 17 days before reaching 350 Growing Degree Days (GDD) following crop cut-out (with a base temperature of 60 °F or 15.6 °C for cotton) allowed for an earlier harvest without any yield decrease in both furrow irrigation and pivot systems.

The authors of [109] conducted a 2-year experiment in the Bekaa Valley of Lebanon under a Mediterranean climate and found that by terminating irrigation permanently at the first open boll, a higher cotton lint yield (639 kg ha$^{-1}$) was obtained compared to early boll loading (577 kg ha$^{-1}$) and mid boll loading (547 kg ha$^{-1}$). Notably, cotton lint yields were reduced as the water amount increased. In fact, the amount of water supplied to the plots where IT occurred at the first open boll opening was 549 mm, compared to 633 and 692 mm for early boll and mid-boll loading, respectively. Additionally, the WUE was found to be higher at the first boll opening treatment (1.3 kg ha$^{-1}$ mm$^{-1}$), followed by early boll opening (1.1 kg ha$^{-1}$ mm$^{-1}$) and mid boll opening (1.0 kg ha$^{-1}$ mm$^{-1}$).

In a study carried out in the semi-arid climate of southwest Oklahoma (USA) [110], the effects of IT on yield and fiber quality were assessed. The results showed that earlier IT treatments achieved average reductions of 16–28% in irrigation requirements during the three growing seasons, but it resulted in a lower production (347 kg ha$^{-1}$ on average) compared to the latest IT treatment. Moreover, early IT yielded significantly smaller grain than under the latest IT treatment. The authors of [111] conducted a 2-year experiment in an arid region of Bathinda (India) and observed that a delay of the last irrigation from 130 to 170 Days After Sowing (DAS) resulted in an increase in cotton grain yield of 14%, 32%, and 8% in the first, second and third year, respectively. Cotton IT is also dependent on the soil type and genotypes. The authors of [104], in a five-year study conducted in the semi-arid region of the San Joaquin Valley of California (USA), found that cotton grown on clay loam soils had a high water-retention capacity. This is because a higher water availability leads to excessive vegetative growth, which make it difficult to defoliate and delays capsule maturity.

The authors of [108] also highlighted that the choice of the genotype heavily influenced IT management. Their field experiments conducted in Arizona (USA) showed that some genotypes responded more to IT than others in terms of cotton yield. In fact, for the Upland cotton genotype DPL 20, an early IT (18 August) or late IT (9 September) did not cause significant differences in terms of harvest, but this was not the case for Prima cotton genotype S-6, where an early IT (12 August) resulted in a 27.6% decrease in production compared to a delayed IT (1 September).

We observed that early IT in mild climatic areas was more successful when compared to the arid areas of Bathinda (India) and semi-arid areas of southwest Oklahoma (USA) [110,111]. Although it has not yet been suitably noted, this represents a key aspect when it comes to growing cotton under an organic regime. The studies conducted in [108] in the humid subtropical climate of Mississippi (USA) and in [109] in the Mediterranean climate of Lebanon highlighted how such climatic areas are more suitable for cotton harvesting in organic systems without the use of chemical treatments, while also reducing irrigation inputs without affecting the cotton grain yield. Figure 5 shows the key points of the main results on this topic.

**Figure 5.** Key findings on irrigation management.

## 4. Final Remarks

This paper analyzed the complexities involved in implementing sustainable cultivation of cotton in different farming systems around the world. This allowed us to highlight different agronomic strategies and tactics pertaining to various cropping regions, all leading towards the same goal of sustainability. Firstly, the plant–microorganism relationships were evaluated, highlighting the potential role of mycorrhizal symbiosis in sustainable cotton production. It was observed that certain combinations of AMF species of the genus *Glomus* can enhance the absorption of different key mineral nutrients for the plant, including not only P and Zn, but also N, K, Ca, Mn, Fe, and Cu. Moreover, the species *F. mosseae* and *G. margarita* were found to affect the abundance of the soil microbiome, while *R. clarus* was shown to increase biomass. Therefore, the identification of the right species and their combinations may be crucial to reducing agronomic inputs and promoting more sustainable cotton cultivation. Secondly, the use of different plant species in farming systems with cotton was analyzed (polyculture vs. monoculture). It was observed that legume cover crops can fix nitrogen and increase labile nitrogen levels in the soil, potentially reducing the need for nitrogen fertilization. However, legumes may have low persistence due to a low C/N ratio, unlike cereals and brassicas. On one hand, cereals such as *T. aestivum* can improve the soil structure and reduce erosion, but they may not have as strong an effect on nitrogen nutrition. Brassica cover crops (*B. carinata* and *O. violaceus*) can reduce weeds and increase soil organic matter, and the total and available nitrogen content. Additionally, brassicas can release allelopathic compounds that affect cotton bollworms. Overall, using different cover crops may offer a balance between the benefits and drawbacks of each species. Third, the irrigation systems most relevant to cotton farming were examined in order to optimize water resources. It was evident that DI systems implemented in different climatic areas were more effective than the more common FI systems in terms of WUE, shoot biomass, and cotton grain yield. Even better results were reported in DI systems supported by plastic mulching films, with significant improvements in terms of soil moisture content, biomass production, and cotton yield compared to DI. Lastly, the review examined the timing of irrigation in organic cotton cultivation systems. It was highlighted that early IT in mild climatic areas, particularly in humid subtropical and Mediterranean climates, can be effectively employed to decrease irrigation inputs without affecting grain yield.

In conclusion, sustainable cotton cultivation represents a crucial option for more responsible management of natural resources. This paper summarized the main recent innovative results obtained by applying various sustainable farming strategies and tactics in different climates without sacrificing productivity. It is hoped that this paper can also guide farmers as, despite scientific evidence, these simple agronomic practices are not widely adopted worldwide. Mycorrhization is still not extensively practiced, the use of herbicides and pesticides often follows a set schedule, irrigation systems are outdated and inefficient, and irrigation termination is not yet seen as a valid alternative to the use of chemical defoliants in areas where climate conditions permit it. It is important to note that, despite the scientific evidence presented, the topics covered in this study require further scientific investigation and longer-term trials to reach a deeper comprehension and to fully grasp the interaction of various factors affecting sustainable cotton cultivation.

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