

AGRONOMY & SOILS

Current State and Future Directions of Tillage Practices in Cotton-Based Cropping Systems: A Comparative Systematic Review Between Sub-Saharan Africa and Other Production Regions

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ABSTRACT

Faced with declining soil fertility and the challenges of climate change, tillage practices in rainfed cotton systems have been improved to adapt to the pedoclimatic conditions of cotton-growing regions. The multiplicity of studies carried out on tillage practices in cotton-based cropping systems in different regions of the world calls for an interdisciplinary systematization of the different research directions, scales of analysis, and reference data used. The aim of this work is to systematically review the contributions of the various studies on tillage, presenting a synthesis of the diversity of practices and the scope of research and knowledge, and identifying the main areas of research according to cotton production regions. From an initial search of 707 articles, 111 met the eligibility criteria for this systematic review. Our analysis revealed that 97.8% of the articles were published between 1995 and 2023, and that most of the case studies were carried out in four climatic zones: subtropical (43.2%); temperate arid long-season and arid short-season with 22.5% and 19.0% respectively; and tropical (15.3%) identifying no-tillage, strip-tillage, and ridge-tillage as the main alternative tillage types to conventional tillage based on plowing. Most research on soil practices focused on soil fertility (40.5%) and cotton productivity (41.4%). These results suggest the need for future research to improve the implementation of agroecological tillage practices in less represented regions such as sub-Saharan Africa, and to ensure the sustainability of new technologies in developed countries.

Cotton production plays a crucial role in the global agricultural economy, providing livelihoods for millions of farmers and supplying the textile, food, dairy, pharmaceutical, and cosmetics industries with cotton by-products (Egbuta et al., 2017). *Gossypium hirsutum* L. cultivars account for 90% of global production and are of particular importance to poor and marginalized farmers in Africa and Asia (Blaise et al., 2021). However, in all cotton-growing regions of the world, cotton production is limited by a high incidence of pests and diseases (Silva et al., 2018), weed pressure, soil degradation (Eskandari et al., 2018), and climatic hazards such as drought, floods, and heat waves (Abdoulaye et al., 2017).

Even with improved transgenic cotton varieties, the average lint yield achieved in developing countries such as India and Africa and developed countries is approximately 500 and 2,500 kg/ha respectively, compared with the theoretical potential yield of 5,000 kg/ha. The yield gap is largely linked to numerous unbalanced factors in soil and crop management and climate, which induce biotic and abiotic stresses impacting yield (Nachimuthu and Webb, 2017). Soil degradation is a major challenge hampering sustainable agricultural production worldwide, with particular concern for the rainfed production basins in the Sudan savannah region of West Africa, characterized by semiarid conditions (Nafi et al., 2020).

In the context of changing climatic conditions and scarcity of resources (water, nutrients), site-specific soil and water management to improve soil physical, chemical, and biological properties are required to maintain soil-water-plant balance and achieve economic profit and fiber quality from cotton cultivation (Abbas and Ahmad, 2018). Among all soil management practices, tillage is of paramount importance as it deeply affects the physical, organic, chemical, biological, and hydric characteristics of the soil layers as a function of the method of soil

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preparation (e.g., plowing, no-till) (Roger-Estrade et al., 2014).

Plow-based tillage promotes crop growth through preparation of the seedbed and burial of crop residues. This family of practices temporarily improves soil conditions by increasing water infiltration rates, soil aeration, organic matter decomposition, weed suppression, and pest control. Considering economic (labor costs and time), environmental (nutrient leakage, water use efficiency, benefits for biodiversity), and agronomic (yield and production quality) factors, tillage use raises fundamental questions about its impact on the resilience of cropping systems. Excessive tillage leads to degradation of soil structure through the reduction of aggregate size (Peterson et al., 1998) and organic matter the soil contains (Tivet et al., 2013), leading to a less stable soil that is more prone to water and wind erosion and compaction (Gupta and Allmaras, 1987). Soil degradation reduces soil quality and crop yield (Abdullah, 2014). This situation requires relevant decisions of soil management in cotton-based cropping systems to avoid degradation threatening cotton production sustainability.

This literature review identifies current research trends in tillage practices for cotton-based cropping systems, while highlighting gaps and challenges to be overcome. To this end, this review will provide answers to the following questions: 1. What is the diversity of tillage practices in cotton-based cropping systems? 2. What are the effects of different tillage practices on the main components of cotton-based cropping systems? 3. How have scientific advances influenced the evolution of tillage practices in cotton-

based cropping systems? 4. What are the gaps and challenges in current research on cotton-based cropping systems?

SYSTEMATIC REVIEW METHODOLOGY

Search Strategy, Keywords, and Selection Criteria. To gather relevant data for this literature review, two databases, namely SCOPUS (<https://www.scopus.com/search>) and DIMENSIONS (<https://www.dimensions.ai>), were explored. These databases were consulted because they are among the largest databases including primary articles, reviews, books, and conference reports (Caviggioli and Ughetto, 2019). This literature review followed the framework developed by Koutsos et al. (2019). Using the keywords of the research theme, a Boolean search equation based on the Population-Outcome model with designed keywords “cotton and cropping systems” for Population and “tillage practices” for Outcome was established and tested in the SCOPUS and Dimensions databases (Petrokofsky et al., 2015) (Table 1). Data were downloaded on 21 October 2023, with the search equation set up by titles, abstracts, and keywords.

Data Analysis. Publication trends by country and continent. A total of 370 documents were extracted from Scopus and 337 from Dimensions. These files were exported in RIS and CSV formats, then processed using R software to eliminate duplicates and perform bibliometric analysis using the bibliometrix package. Bibliometric analysis, considered a methodical and unbiased approach to reviewing literature, enables the identification, evalu-

Table 1. Model Population and Outcome (PO)

Key Element	Description	Keywords and Synonyms Search	Syntax to be used per element
Population	Cotton production systems	cotton, gossypium hirsutum, Gossypium hirsutum L., Gossypium AND cropping system, cultural system, production system, farming system, agrosystem	cotton OR "gossypium hirsutum " OR "Gossypium hirsutum L." OR gossypium*) AND ("cropping system" OR "cultural system" OR "production system" OR "farming system" OR agrosystem*)
Outcome	Tillage system for cotton cultivation	Tillage, soil management, Agricultural cultivation methods, Farming practices, soil preparation, Soil tillage techniques, Soil management systems, Plowing methods, Land preparation systems, Field cultivation approaches, Soil cultivation strategies, Ground preparation techniques	(tillage OR "soil management" OR "Agricultural cultivation methods" OR "Farming practices" OR "soil preparation" OR "Soil tillage techniques" OR "Soil management systems" OR "Plowing methods" OR "Land preparation systems" OR "Field cultivation approaches" OR "Soil cultivation strategies" OR "Ground preparation techniques")

ation, and interpretation of relevant studies available on a specific research question in a particular field of study or related to a problem of specific interest (Salinas-Ríos and Janneire García-López, 2022). Consequently, analysis of publication trends in the research field was carried out using the bibliometrix R tool via the biblioshiny interface (Aria and Cucurullo, 2017). This analysis provided the annual rate of publication on cotton-based cropping systems and detailed trends in the number of publications over time, covering the years 1984 to 2023.

Criteria for inclusion and exclusion of documents in CADIMA. A corpus of 444 documents, stripped of duplicates using CADIMA, a web-based tool that facilitates the conduct and ensures the documentation of journals, systematic maps, and other literature reviews, was subjected to an initial filtering phase. This process involved assessing the relevance of documents based solely on title and abstract (Petrokofsky et al., 2015). Thus, documents were considered eligible if they simultaneously met the Population and Outcome criteria: they all related to cotton cultivation and the methods of tillage or soil management used in cotton farming. Any paper that did not meet one of these criteria at the first stage was excluded. In addition, articles evaluating irrigation were excluded, as this review focuses on rainfed cotton. In the event of uncertainty, the article was retained for further evaluation (Garca-Yi et al., 2014). At the end of this stage, 304 papers were advanced to the second stage (Fig. 1).

The second stage consisted of an assessment of the relevance of documents after full reading and examination of their eligibility conditions. Documents were eligible if they met both the Population and Outcome conditions and had an accessible Pdf file. Any document failing to meet one of these conditions at the second stage was excluded. A total of 111 documents were selected for systematic review (Fig. 1). After full-text evaluation, documents included in the study were subjected to an extraction of relevant data in accordance with the format imposed by CADIMA. The extracted information covered various aspects, such as major advances and key dates, distribution of publications by country/continent, tillage methods, cropping systems and their effects on soil fertility, productivity, pest and weed management, and cotton breeding, specific limitations (constraints and challenges mentioned by the authors), the implications of these limitations on productivity, identified gaps (aspects not covered or poorly understood according

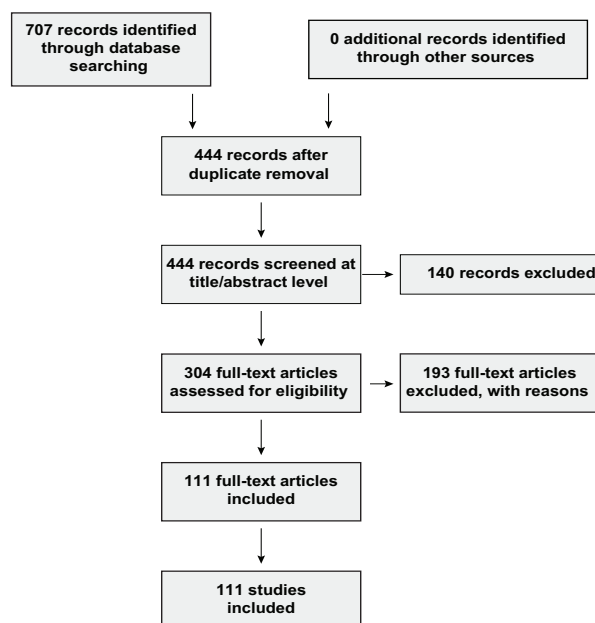


Figure 1. Flow diagram for inclusion criteria compliant with reporting standards for systematic evidence syntheses (ROSES) standards in tillage systems in cotton-based cropping systems.

to the authors or arising from the analysis), recommendations for future research (specific proposals from the authors), and identified opportunities (areas with research potential, arising from the analysis). After data collection, the database was extracted and processed. Some data were used to generate graphs of citation frequencies in Excel, whereas others were used to develop a narrative synthesis to address the research questions raised by this systematic review.

RESULTS AND DISCUSSION

Brief History of Tillage Practices. Soil tillage is a set of mechanical operations that modify the physical structure of surface horizons and plays a key role in agroecosystems. The history of tillage dates from the Neolithic period with the invention of agriculture. The need to produce food and services required for human survival led to the transformation of natural ecosystems into more productive agroecosystems. Thus, the first soil-working implements were agricultural tools such as sticks, hoes, and implements designed to stir up the soil to limit competition from weeds, and make soil resources available to cultivated plants, thus increasing productivity (Leroi-Gourhan, 1957). As human strength was insufficient, societies gradually mastered animal

traction (cattle, horses) with the invention of plows (Griffon, 2013). In many parts of the world, particularly in Africa, animal traction continues to provide the energy needed to work the soil.

At the end of the 19th century, animal traction was replaced by motorized traction thanks to the use of petroleum. Today, these three power sources support tillage methods (human, animal, and motor) used in cotton-growing regions around the world, depending on the farmer's means and access to technology. Manual plowing with a hoe or similar implement continues to be the dominant practice of soil tillage in Africa. The widespread replacement of manual labor by animal and motorized traction is in full swing and will transform the face of African agriculture as it did in the world's first mechanized countries (Daum et al., 2021). Animal-drawn and motorized tillage methods include plowing, ridging, and scarifying carried out using moldboard plow, disc plows, chisel plows, and harrows pulled by animals and tractors (Carruthers and Rodriguez, 1992).

Diversity of Tillage Practices. A variety of tillage practices and cover crops have been developed around the world to suit local soil and climate conditions. Tillage can be conventional, based on plowing with deep soil inversion (22-50 cm depth) using appropriate tools (Atique-ur-Rehman et al., 2020). Although differences occur according to production zone, these systems generally consist of adapted tillage tools that bury almost all remaining crop residues and disturb the entire soil surface. Soil loss due to wind and water erosion has led to the development of conservation tillage (Bauer, 2015). Conservation tillage is a set of tillage practices including mainly ridge tillage and strip tillage with limited soil disturbance and allowing 30% or more of the soil surface to be covered with plant residues after planting (Bergtold et al., 2020). The depth of tillage, the effect that the tool used has on the soil and crop residues, as well as the proportion of the plot surface tilled, are decisive criteria for categorizing conservation tillage practices (Ali et al., 2020; Roger-Estrade et al., 2014) (Fig. 2).

In addition to tillage practices, crop residue management and species diversity in rotations play an important role in protecting soil resources and improving their chemical, physical, and biological fertility. Conservation agriculture strives toward integrated soil fertility management and is based on three principles (Kassam et al., 2019): (1) adopting a conservation tillage system; (2) introducing species

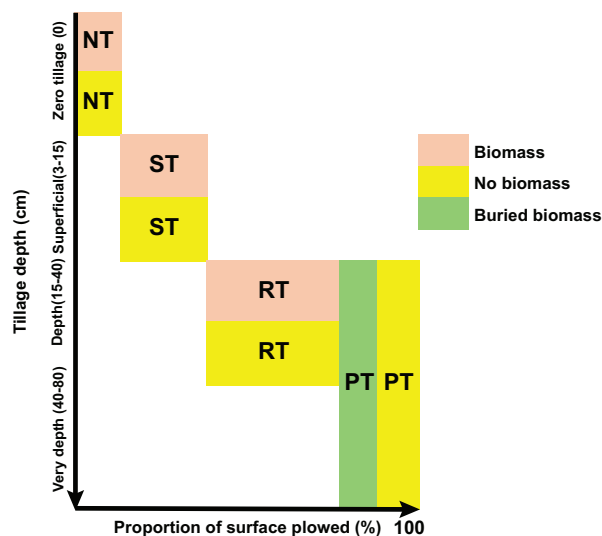


Figure 2. Tillage practices classification for cotton: plow-based tillage (PT); ridge tillage (RT); strip tillage (ST); no tillage (NT). Adapted from Roger-Estrade et al. (2014) and Ali et al. (2020).

diversification through rotations, cover crops, and intercrops; and (3) maintaining sufficient soil cover across the year made up either of dead residues from the previous crop or cover crop, or of living mulch.

Main Cotton-Growing Systems and Production Environments Worldwide. Climatic characteristics such as the length of the growing season and water availability affect cotton growth. Climatic zones for cotton production are divided into groups based on season length and water availability: long-season and humid in tropical, short-season and humid in subtropical, long-season and arid in temperate, and short-season and semiarid in temperate (Conaty et al., 2015). A growing season of more than 150 days is defined as a long season, and less than 150 days as a short season.

Cotton-growing systems are diversified in terms of management practices and the nature of crop rotation, as well as their environmental impact. Depending on agroclimatic conditions and access to technology, different strategies are implemented in the main producing countries to ensure profitability and sustainability of cotton production. In developed countries such as the U.S., Brazil, Australia, and China, cotton production systems are intensive in fertilizer use and highly mechanized. Cotton is irrigated in some areas of these countries with greater than 80% of the area in Australia (CNUCED, 2016; Roth et al., 2013). However, in southern countries, particularly in Africa, cotton production is extensive,

and a labor-intensive activity is carried out by small producers lacking mechanized equipment. Cotton production is typically rainfed and low input, often rotated with staple or commercial crops such as *Zea mays* L., *Arachis hypogaea* L., *Glycine max* L. (Merr.), and *Vigna unguiculata* L. (Walp) (Amanet et al., 2020).

How Have Scientific Advances Influenced the Evolution of Tillage Methods in Cotton-based Cropping Systems? Trends in publication. Three hundred and seventy studies devoted to methods of tillage in cotton-based cropping systems published between 1984 and 2023 comprising 328 articles and 42 literature reviews were analyzed. Exclusively written in English, this research indicates a growth trend in annual production linked to tillage methods in cotton-based cropping systems during this period, with an annual growth rate of approximately 5.8% (Fig. 3). Analysis of the time series of publications

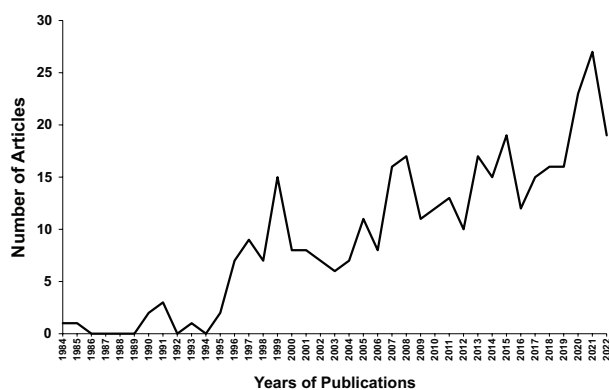


Figure 3. Dynamic evolution of publications in tillage systems in cotton-based cropping systems.

on this topic suggests a subdivision of studies into two main research periods. The first period, 1984 to 1994, was characterized by low scientific production on the subject. The annual rate of scientific publication was slow, with little variation before the start of the second period (2.2%), suggesting that research on tillage practices in cotton cropping systems was not yet a matter of great concern. This trend was significantly reversed (97.8%) during the second period (1995-2023), with an increase in scientific production on the subject.

To offset the adverse effects of plow-based tillage on the physico-chemical and biological properties of the soil, direct sowing was tested and developed in the U.S. beginning in 1960 (Raunet, 2004). The need to control weeds without tillage and a lack of

broad-spectrum herbicides applied postemergence on cotton farms contributed to the development and spreading of transgenic cotton cultivars resistant to the herbicide glyphosate in the southeastern U.S. in the mid-1990s (Buman et al., 2005; Rocha-Munive et al., 2018). This technology eased the development and adoption of soil conservation practices on cotton farms in other countries such as Argentina, Brazil, and Paraguay (Triplett and Dick, 2008). Cotton grown using conservation agriculture practices increased rapidly, with more than 66% of cotton growers using soil conservation practices (Mollae et al., 2020). This technological breakthrough has stimulated research into tillage practices and sparked renewed interest in research into other forms of tillage with adaptation and tool development in cotton-based cropping systems.

Analysis of the distribution of publications by production system profile. The present literature review also investigated the geographical distribution of studies related to tillage practices in cotton-based systems. The results indicate a significant disparity in publications at a continental level, with subtropical climatic zone contributing 47 (42.4%) articles (Fig. 4). Twenty-five (22.5%) studies were carried out in the temperate climatic zone marked by a long-season arid and 22 (19.8%) in the short-season arid part of the zone. For these three climate zones, most articles come from the U.S., followed by Pakistan and Australia. The main climatic challenge for growing cotton in these environments was water supply, with average-to-low annual rainfall (ranging from 24 to 590 mm) (Conaty et al., 2015). The predominance of tillage studies in these regions is indicative of the search for solutions to deal with this rainfall constraint. Conservation agriculture for cotton was implemented as early as 1981 at the University of West Tennessee Research and Education Center in Jackson, TN (Hu et al., 2021).

In the tropical zone, which includes several African countries and Brazil, the number of publications is low, 17 articles (15%). In this zone, rainfall is significant and should not be considered a constraint given an average annual rainfall of 790 mm (Conaty et al., 2015). The constraint lies rather in its temporal distribution, added to the problem of organo-biological fertility due to low restitution of fresh organic matter in sub-Saharan Africa (Corbeels et al., 2020) and rapid degradation of soil organic carbon. These geographical disparities in cotton production research represent opportunities

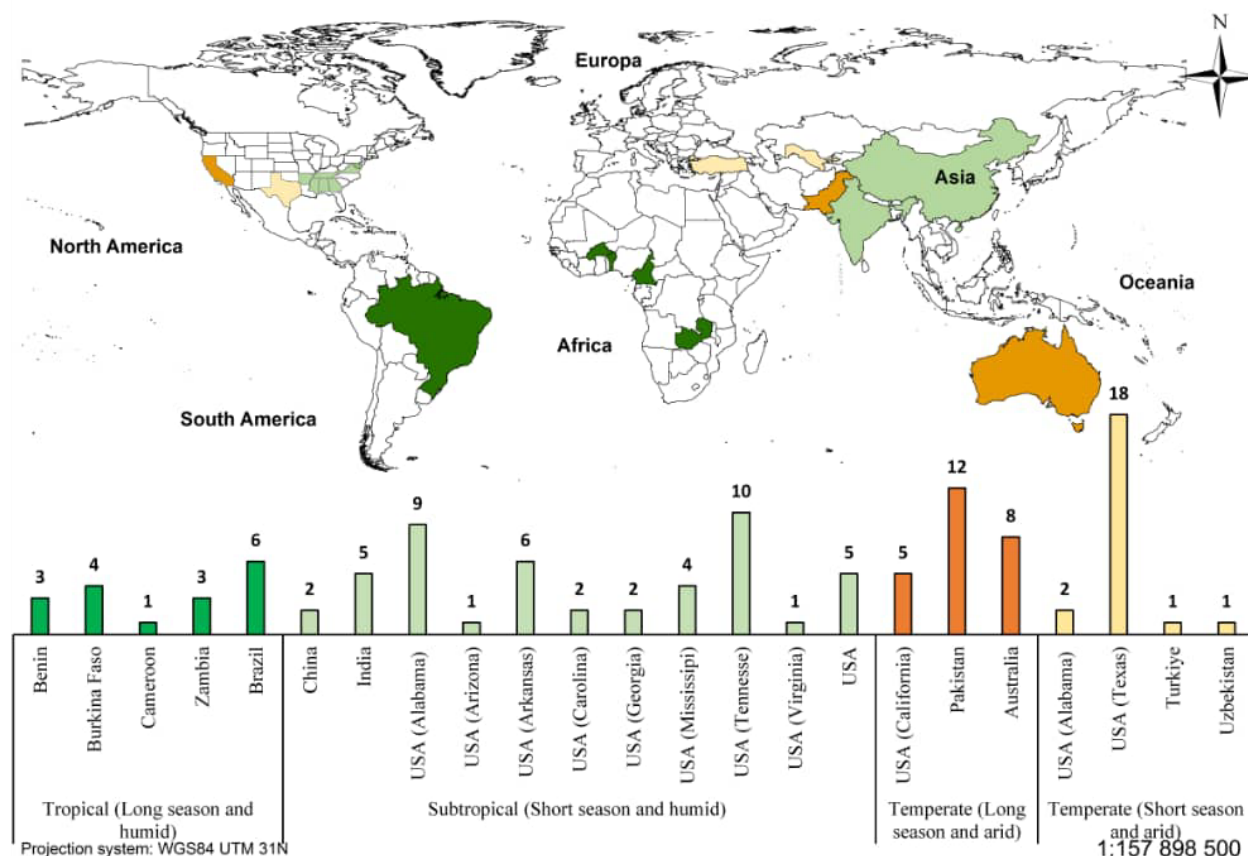


Figure 4. Cotton-growing regions and production environments coverage of articles studied.

for some and challenges for others in terms of the progress to be made through dedicated research and exploring more avenues for a profitable cotton production system.

Analysis of studies on tillage practices reveals significant differences in farming practices studied. The two extreme tillage systems are the most studied, with plow-based tillage and no-till accounting for 41.2 and 37.9% of the sample, respectively (Fig. 5). These high proportions demonstrate that plow-based tillage continues to be standard in many cotton-growing regions. A research trend towards no-tillage practices indicates a desire to optimize yields while minimizing impact on soil and the environment. Strip tillage is the second most studied form of soil conservation practice (13.7%) followed by ridge tillage (7.2%). The subtropical zone is the most represented in all tillage practices, followed by temperate zones and finally the tropical zone. Among alternative tillage practices to plow-based tillage, no-tillage ranks first in subtropical and tropical zones. In conclusion, the analysis of tillage systems highlights the diversity of alternative tillage practices in cotton-based cropping systems and reveals the diversity of practices

between regions, the choice of which could be due to specific soil management considerations in addressing the problems of sustainability and economic performance of cotton farms.

In addition to tillage, other components of cropping systems, such as the specific diversity of crops (rotation, intercropping, cover crops) and the intensity of biomass flows returned to the plot, are ecological intensification actions in conservation agriculture that influence soil quality by enhancing biodiversity within cultivated ecosystems, which in turn improves their resilience. Thus, this ecological intensification of soil contributes to maximizing the provision of ecosystem services by edaphic biodiversity, while minimizing the impact of the ecological mechanisms of successional dynamics, thus conferring greater ecological resilience and sustainability on agrosystems (Chabert and Sarthou, 2019; Yachi and Loreau, 1999).

Main Research Fields on Tillage Practices in Cotton-Based Cropping Systems. Results on the types of studies carried out on tillage practices in cotton-based cropping systems highlight disparities between research fields according to production sys-

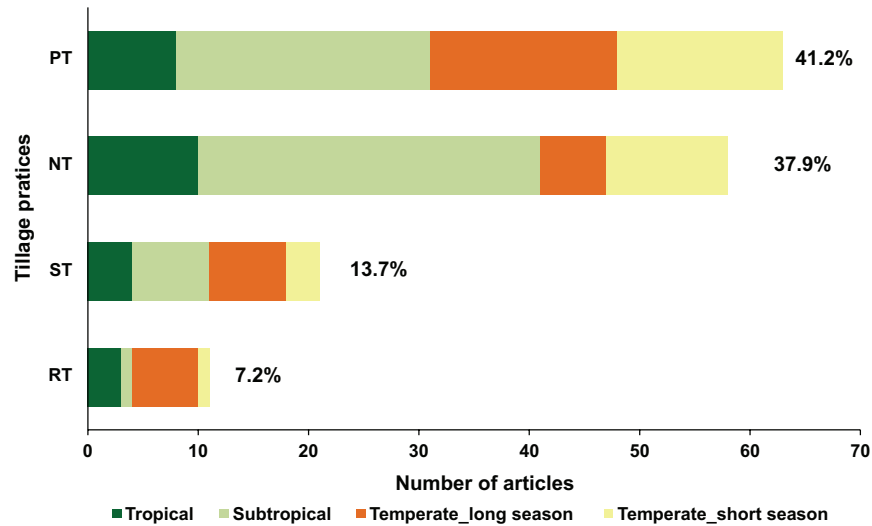


Figure 5. Diversity of tillage systems across the publications under study: plow-based tillage (PT); ridge tillage (RT); strip tillage (ST); no tillage (NT).

tem profile (Fig. 6). This could be due to factors such as limited resources, differing agricultural priorities, and agricultural research needs vary considerably between regions. Irrespective of region, seed cotton productivity and soil fertility are first, with 41.4 and 40.5% of the publications, respectively. Studies on economic profitability of soil practices in cotton-based cropping systems account for 7.2% of articles, compared with 4.5 and 3.6% for research on weed management and cotton fiber quality, respectively. Work on variety performance, pest management, and the adoption of new soil conservation practices accounts for 0.9% of the articles evaluated.

When considering production environments, each climatic zone is represented in five of the eight research areas, especially cotton productivity and soil fertility. A strong representation of subtropical and temperate zones due to the aridity of the locations was present, which affected cotton productivity and all the other corollary research areas. Research into fiber quality is particularly focused on long seasons and in the arid temperate zone. Research into tillage practices in cotton-based cropping systems is less intense in the tropic zone, particularly in Africa, where topics such as cotton varieties, economic profitability, and fiber quality have received little

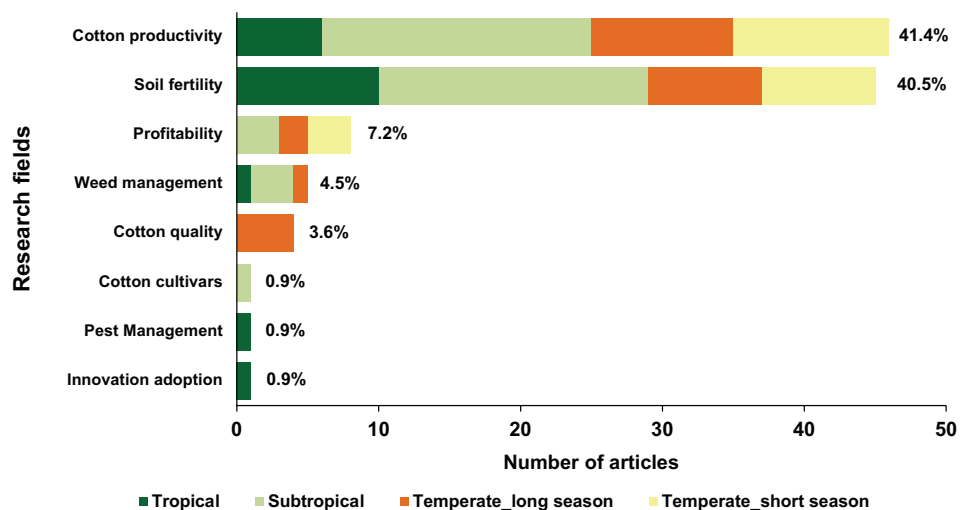


Figure 6. Overview of the thematic research fields by production area.

attention. Indeed, unlike many food crops, little in-depth research has been carried out on cotton in Africa (Amanet et al., 2020). This diversity probably reflects the complexity of agricultural challenges in different cotton-growing regions with diverse climatic conditions and farming practices. Seed cotton productivity and soil fertility appear to be two subjects of major interest in all regions, underlining the universal importance of maintaining fertile soils to sustain agricultural production.

Improving soil fertility. Moisture, temperature, porosity, bulk density, soil structure, organic carbon content, and soil biodiversity are among the soil properties affected by tillage (Sathiya Bama et al., 2017). Conventional tillage practices involve intensive and repeated tillage operations. Burning or low residue restitution have led to deteriorating soil health and lower crop productivity in cotton-based cropping systems. In most tropical cotton-producing countries in Asia and Africa, cotton stalks are considered waste and destroyed by burning (Blaise and Ravindran, 2003), and this practice has reduced soil organic matter content (Kintché et al., 2010). Alternatives, such as strip tillage and no-till associated with cover crops are being evaluated as potential solutions for soil moisture conservation (Blanco-Canqui et al., 2015) and limit soil loss through erosion, thus preserving soil organic carbon and increasing crop yields (Gathagu et al., 2018).

Lower seed cotton yields were observed after cover crop use due to increased moisture deficit at planting in the Southern Great Plains region, U.S. (Lewis et al., 2018). Results obtained by Burke et al. (2022) in the semiarid High Plains of Texas, have challenged the assumption that cover crops limit water availability during active cotton growth. Although soil water was initially depleted by cover crops, it was more important throughout the cotton growing period. Better water infiltration (48.5 mm h^{-1}) in conservation farming systems in Zimbabwe compared with 12.6 mm h^{-1} in conventional systems was reported by Mhlanga and Thierfelder (2021). However, producing sufficient biomass of good quality to produce the potential benefits can be a challenge in semiarid cropping systems where water resources are limited.

In a soil-conserving practices approach, maintaining crop residues on the soil surface in cotton-based cropping systems where cotton is known to have few crop residues remains a challenge. Thus, several crops are rotated with cotton worldwide,

such as *Oryza sativa* L. and *Triticum aestivum* L. in Pakistan, northern India (Das et al., 2004), and Uzbekistan (Kahriz et al., 2020); *Glycine max* L. (Merr.) in Brazil (Hoffmann et al., 2020); and maize in the U.S. (Nouri et al., 2019) and in other cotton-growing regions such as Africa to improve soil structure. These crops generate a substantial quantity of crop residues to improve soil fertility (Blaise et al., 2021). Grasses are generally a good rotational crop for cotton. Maize sown in rotation with cotton reduced nitrogen leaching and improved its use efficiency by cotton (Nachimuthu et al., 2019), and increased soil organic carbon stock in Australia (Osanai et al., 2020, 2021). Irrespective of tillage, the addition of winter wheat to the cotton rotation improved soil organic carbon stock in a long-term study conducted at the University of Tennessee (Patra et al., 2022).

Integrating the grass, *Urochloa ruziziensis* (R. Germ & C.M. Evrard), as a cover crop into a cotton/soybean/maize rotation combined with zero tillage on an oxisol in the Cerrado region of Brazil, improved soil organic matter levels and potassium storage capacity after nine years of cropping system experimentation (Ferreira et al., 2022a). Similarly, a 15-year no-till crop and cover crop rotation experiment conducted at the University of Tennessee revealed that cotton-corn rotations improved soil quality index based on pH, bulk density, soil extractable phosphorus and potassium, hydraulic conductivity, and sodium adsorption rate, compared to the rotation including soybean (Amorim et al., 2020). In a long-term simulation study of the impact of no-till association with cover crops in cotton-based cropping systems in Texas, Ashworth et al. (2020) and Singh et al. (2023) highlighted the biomass-producing potential of *Vicia villosa* L. (vetch) and *Pisum sativum* L. (pea) species with high total nitrogen levels inducing an improvement in soil organic carbon stock. After 19 years of experimentation in Lamesa, TX, Burke et al. (2019) found that two conservation agriculture practices, no-tillage rye cover and no-tillage mixed species cover had no impact on soil inorganic total nitrogen in sandy soil, although the amounts of organic carbon and oxidizable carbon were higher.

The integration of livestock farming into conservation agriculture through short-term grazing of crop residues studied in the coastal plains in Alabama failed to produce results after two years in view of the decrease in microbial carbon biomass on grazed plots (Crowell et al., 2022). However, the same authors found that this decrease in microbial biomass had no

impact on soil physico-chemical properties such as soil organic carbon, potassium permanganate oxidizable labile carbon, and water aggregate stability. For soil conservation tillage to be more effective, tillage must consider the topographic properties of the land upon which cotton is grown. Indeed, a study carried out in Benin and Burkina Faso under a cotton-maize rotation showed the need for ridging along contour lines with incorporation of crop residues on soils at the bottom of slopes to improve soil organic carbon, total nitrogen, phosphorus, and potassium stocks (Nafi et al., 2020).

In Brazil, an assessment of the impact of cotton production systems on soil quality in the Cerrado revealed better carbon (59 Mg ha^{-1}) and nitrogen (3.5 Mg ha^{-1}) levels in areas with widespread use of conservation agriculture (Dos Santos et al., 2020), and an annual rate of carbon increase of 2.36 Mg ha^{-1} for five years in a sandy no-till soil under a cotton-soybean-corn rotation incorporating cover crops (Ferreira et al., 2022b). In addition, the practice of zero tillage with the presence of cotton, wheat, and maize residues conducted for four years in the plains of New Delhi, India, resulted in better soil aggregation and greater nitrogen accumulation in macroaggregates (Bhattacharyya et al., 2019) indicating that the nitrogen fertilizer rate might not be reduced in a sandy-loam soil over a short period of conservation agriculture.

Cotton productivity. In cotton-based cropping systems, the use of cover crops combined with no tillage does not always improve seed cotton or fiber yields. Indeed, previous studies have shown divergent results. The result depends on several factors, including cover crops selection, crop management conditions, rainfall, the length of time the practice is applied, and the soil type (Billman and Campbell, 2023; Decker et al., 2022; Foote et al., 2014; Toler et al., 2019). Previous studies have shown that cotton yields in reduced-till and no-till systems are comparable to cotton grown in conventional systems (Daniel et al., 1999; Denton et al., 2021; Fan et al., 2020; Ouattara et al., 2021; Singh et al., 2023) especially in a short period (Spivey et al., 2019).

The use of cover crop species in cotton production varies according to the geographical location of the cotton-growing areas. A study carried out in Burkina Faso showed that over 10 years, no-till with or without a cover crop provided seed cotton yield that were statistically equivalent to the tillage commonly practiced by farmers (Ouattara et al.,

2021). These results highlighted the low contribution of legumes (*Mucuna cochinchinensis* Lour and *Crotalaria juncea* L.) to soil nitrogen content in the upper layers of direct seeding mulch cotton cropping. The results of a meta-analysis of studies carried out in U.S. cotton-growing regions revealed the use of several cover crops: *Avena* spp., *Brassica* spp., *Lupinus* spp., *Pisum* spp., *Secale* spp., *Trifolium* spp., *Triticum* spp., and *Vicia* spp. (Toler et al., 2019). According to this synthesis cover crops increased seed cotton yield by an average of 6% for all tillage systems. These authors found cover cropping had little effect on seed cotton yield in no tillage (+5%) and conservation tillage (-2%) systems. However, the incorporation of cover crops by tillage resulted in an average 10% increase in seed cotton yield. In a study carried out in the Mississippi region of the U.S., Denton et al. (2020) found cotton lint yield did not differ due to cover crop species. The cover crop species studied (crimson clover, *Trifolium incarnatum* L.; cereal rye, *Secale cereale* L.; oat, *Avena sativa* L.) did not improve cotton productivity (Denton et al., 2021). But cotton yield increased 8% when cover crop termination was delayed from February until May (Denton et al., 2020).

In Brazil, in the state of Mato Grosso, improved chemical soil fertility through nitrogen fixation due to diversification of crop rotations under zero tillage and improved water availability below soil depths of 0.2 to 0.4 m generated an 18% gain in seed cotton yield (Anghinoni et al., 2019). In a no-till soybean-maize-cotton rotation, in combination with cover crops, improved chemical soil fertility through nitrogen fixation increased cotton and soybean yields (Ferreira et al., 2022b). Other studies have shown that soil conservation practices have not significantly improved seed and lint yields in the U.S. (Burke et al., 2022; Singh et al., 2023), but significantly improved cotton productivity under drought conditions (Foster et al., 2018) enabling growers to stabilize their net profit (Fan et al., 2020).

Limited seed cotton yield penalties were observed in conservation agriculture in Benin during the first year of the agroecological transition (Yemadje et al., 2022), suggesting that the benefits of this soil management method could be observed only after several years of practice. Despite these potential agronomic and environmental advantages over the tillage systems, agronomic difficulties are associated with no-till, including poor seedling emergence, less vigorous seedlings, insufficient root penetration, and

poor crop growth due to soil compaction (Gwathmey et al., 2010; Peixoto et al., 2020; Schwab et al., 2002) (Fig. 7). Moreover, it can take up to three years for the no-till system to become fully functional when switching from a plowed to a no-till crop (Triplett and Dick, 2008). Consequently, the long-term use of no-till and conservation agriculture, with cautious attention to soil physical conditions during initial years, should be encouraged to achieve these benefits.

Weed management. Weeds reduce the productivity of many crops, including cotton. One of the recognized advantages of plow-based tillage systems is weed control. Under reduced or no tillage, weed management becomes a challenging task, as the ecology and dynamics of weeds are different from that in plow-based tillage (Peixoto et al., 2020). Broad-spectrum herbicides based on haloxyfop + lactofen revealed their effectiveness on weed control in a sandy-loam soil in Pakistan regardless of the cropping system (Usman et al., 2013). Weed species have become increasingly resistant to glyphosate since the advent of glyphosate-resistant cotton cultivars in 1997 (Steckel and Gwathmey, 2009).

In conservation agriculture, crop diversification and sequence can help manage weeds and maintain soil fertility (Naeem et al., 2021). The use of cover crops producing maximum biomass could suppress or delay weed emergence, thereby reducing the critical control period, (Korres and Norsworthy, 2015). A study in Alabama revealed that the presence of a rye

cover crop delayed the critical time for weed control by approximately eight days, compared with 14 days for plow-based tillage (Price et al., 2018). The results of a meta-analysis revealed that weed biomass decreases by an average of 20% with cover crops (Toler et al., 2019). In this analysis, the cover crops, *Triticum* spp. and *Secale* spp., provided a reduction in weed biomass of 37% and 21%, respectively. In addition, it is essential to optimize the choice of other biological components of the agrosystem to improve weed management. Cotton varieties associated with cover crops contribute to weed management and this means that a seeding rate adapted to the cotton variety would help to prevent development of weeds thanks to the competitive power of the cotton variety. Cover crops reduced weed biomass by 16% on average in the Stoneville cultivar, and by 22% in the Deltapine cultivar (Toler et al., 2019). For high seeding rates applied to cotton cultivars Fiber Max 960RR (124,000 plants ha⁻¹), Campo (185,000 plants ha⁻¹), and Sicot 289BR (147,000 plants ha⁻¹) the reduction in weed density was 49% (Duggan et al., 2005; Moran and Greenberg, 2008; Vasilakoglou et al., 2011).

Adoption of conservation tillage practices. The only publication dealing with the adoption of conservation tillage relates to a study carried out in Zimbabwe on minimum tillage. According to this study, the use of minimum tillage by farmers in this country is linked to greater availability of herbicides and to reduce vulnerability to unpredict-

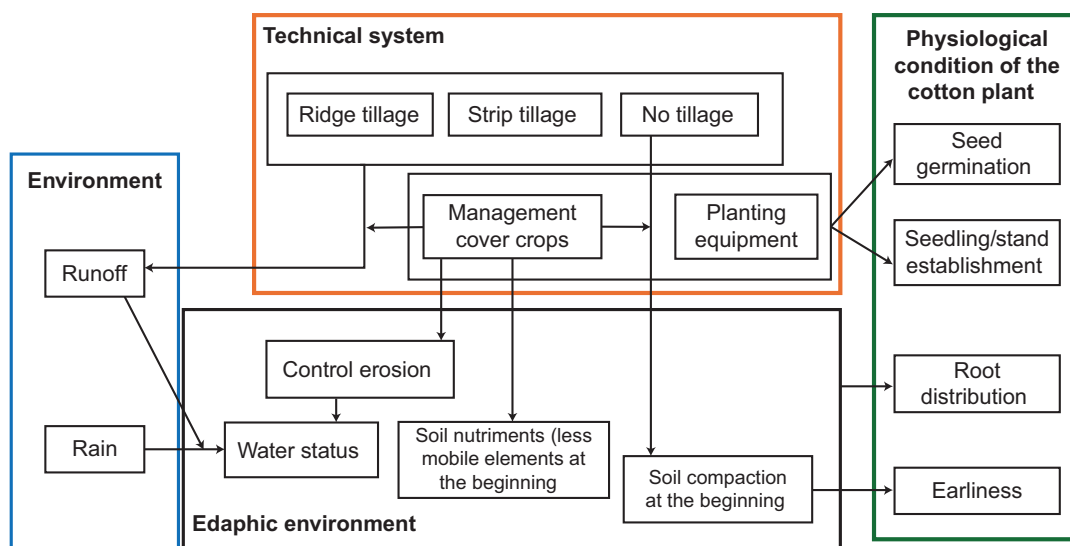


Figure 7. Ecophysiological responses of cotton to soil tillage systems and cover crop management. Adapted from Gwathmey et al. (2010).

able climate (Grabowski et al., 2016; Ngoma et al., 2015). With an area of 12% devoted to cotton and 20% to maize, the rate of adoption of this practice remains relatively low in Zimbabwe. Many farmers are interested in adopting minimum tillage, but the technologies available do not match the socioeconomic resources (low availability of labor, cost of equipment) available to producers. The conditions in which conservation agriculture systems are adopted by small producers in Africa are areas of periodic water stress, where energy and labor are scarce and soil erosion and degradation have become critical (Baudron et al., 2015).

In addition, growers in southern Texas, which represents the largest arid cotton production area in the U.S., where water supply is the principal driver of yield (Foster et al., 2018), have also adopted conservation agriculture systems. In sub-Saharan Africa, the implementation of soil conservation practices in cotton-based cropping systems is hampered by the low mechanization, lack of appropriate tools and technical information, poor weed control, and competition for crop residues in mixed crop-livestock systems (Corbeels et al., 2020; Giller et al., 2009). However, across the U.S., cotton acreage under no-till and strip-till has increased from 33% in 2011 to 40% in 2015 (Wade et al., 2015). But this increase occurred mainly in the humid southeastern U.S., where nearly 70% of cotton was planted under conservation tillage, compared with less than 30% in the Southern Great Plains region (Claassen et al., 2018).

Cotton cultivars. A notable aspect of cotton productivity improvement lies in the introduction of genetically modified varieties. Genetically modified

technology has been adopted mostly in developed countries where cotton yields and productivity are far better than in developing countries (Mollae et al., 2020). This innovation, often associated with conservation tillage (White et al., 2000), is widely used in developed countries (Fig. 8). Its use significantly decreased herbicide use on crops and improved agronomic crop performance (Lu et al., 2012; Witjaksono et al., 2014). Only one publication made a comparative evaluation of the agromorphological performance of conventional and genetically modified varieties in plow-based tillage and conservation tillage systems in the coastal plain region of the U.S. (Balkcom et al., 2010). The results showed that the performance of the varieties evaluated were similar in all cropping systems (no genotype by management interaction).

Genetically modified (GM) cotton, particularly Bt cotton, offers advantages over conventional varieties in terms of reducing insect infestations and improving yields. Studies of soil conservation practices worldwide reveal that the adoption of GM cotton has contributed to a 37% reduction in pesticide use, as well as an increase in crop yield of approximately 22% and profitability of 68% on average, compared with non-GM varieties (Klümper and Qaim, 2014). In recent years, improvements have been made to GM products to enhance their efficacy, extend protection, and reduce resistance. These improvements require investment that technology developers recoup from farmers through trait royalties or fees. As a result, GM products become more expensive; however, their efficacy diminishes over time through repeated use, providing an incentive to pursue the

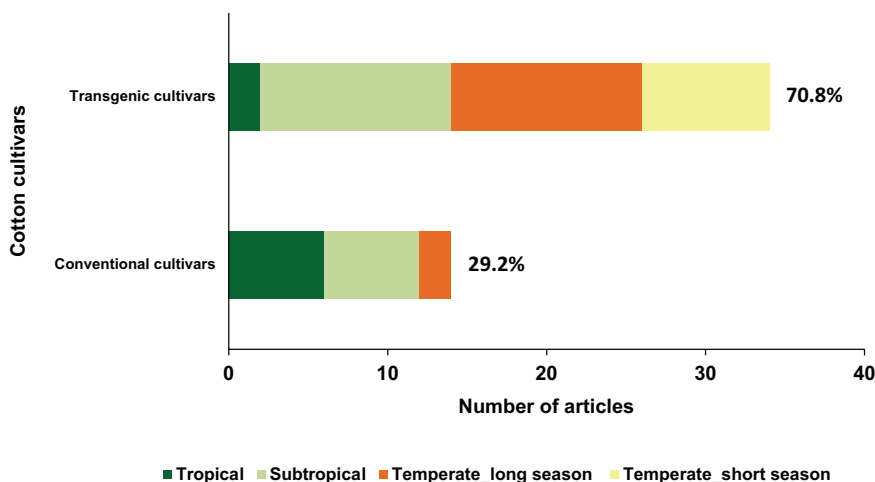


Figure 8. Number of articles specifying the types of cotton varieties used.

gene pyramid (Balasubramani et al., 2021). In addition, it is important to note that there could be differences in fiber characteristics between transgenic and conventional cotton varieties, such as fiber length and resistance, which can impact the marketing of cotton fiber as was the case in Burkina Faso (Bourgou et al., 2020). The differences between the materials compared are genetic and are due to the inability to recover important characteristics after transgenic conversion. Local GM cultivars could certainly be an asset if they were better developed to take account of the specific features of local production.

The benefits of GM varieties have been overstated by some major corporate seed companies, and its widespread adoption is threatened by the problem of the sustainability of herbicide-tolerant variety technology due to the evolution of weed resistance to herbicides in the absence of a diversified weed management program (Kniss, 2018; Thornby et al., 2018). Another potential problem is the reduction in the genetic diversity of cotton varieties due to the large-scale adoption of high-yielding GM cotton under optimal conditions (Liu et al., 2015). Growers in South Africa, Kenya, Sudan, Burkina Faso, Sudan, Nigeria, and Ghana have experimented with GM cotton resistant to insect infestations and herbicide with mitigated results. This situation has not made it possible to experiment and to extend the use of GM cotton on this continent, particularly in sub-Saharan Africa. In West Africa, conventional cotton varieties continue to be widely grown, due to the controversial results associated with the use of GM varieties in terms of proven and unproven risks (loss of biodiversity, development of resistance, cost to growers) (Soumaré et al., 2021).

In many cotton-producing countries in Africa and elsewhere in the world, institutional and political arrangements are not conducive to the testing of transgenic cotton varieties (Nnaemeka and Yuqiang, 2023). In this context, the selection of conventional cotton varieties for the development of conservation agriculture in cotton-based cropping systems remains a challenge and at the same time becomes a contribution to enhance the adoption of conservation agriculture in cotton-producing countries south of the Sahara.

ANALYSIS OF CHALLENGES AND OPPORTUNITIES IN TILLAGE AND COTTON PRODUCTIVITY

Specific Limitations: Constraints and Challenges. The review of the literature concerning studies on tillage practices in cotton-based cropping systems highlights several critical points for improving current systems and developing soil conservation practices. It emphasizes that the effects of conservation tillage on soil properties depend on the given cropping system, including the nature of crop rotation and cover crop species. Furthermore, the impacts of conservation tillage and conservation agriculture on agronomic and environmental parameters at the start of the transition present contradictory results, and few studies have focused on these questions related to transition phase (Blaise et al., 2021). Short-term yield penalties under no-till have been reported, highlighting the need to take these initial impacts into account when assessing the potential for farmers to adopt these practices. Variability in short-term responses is attributed to the complex interactions of crop needs, soil characteristics, and climate (Giller et al., 2009). Regarding cover crops, it was evidenced that site-specific responses on soil and crop productivity are complex to unravel and depend on many environmental and management variables. Research has not sufficiently addressed the diversity of cover crops present in cotton-growing areas. Potential challenges related to intercropping cotton with other crops are little studied in Africa. Current studies do not sufficiently explore the long-term effects of these associated crops on essential soil properties, such as pH, nutrient availability, or microbial activity (Burke et al., 2022). Results in field experiments often neglect intermediate processes, thus limiting a full understanding of the impacts of cover crops (Singh et al., 2023). The absence of detailed information on the grown cultivar highlights a lack of precision in existing studies (DeLaune et al., 2019). Finally, despite the breadth of previous research, much of it has focused on short-term assessments of the effects of tillage, crop residue incorporation, or nitrogen in monoculture systems and at single sites. Comprehensive, multi-site, multi-factorial studies over several growing seasons are necessary to gain a thorough understanding of the interactive effects of tillage and biomass residue management and nitrogen fertilizer application on soil properties (Nafi et al., 2020) and its effects on interaction

between environment, cropping systems, and cotton genotypes. Differences between cotton cultivars affect vigor and seedling establishment (Snider et al., 2016) as well as soil nutrient uptake (Mullins and Burmester, 2010) and must be sufficiently considered in the design of agroecological cropping systems (Gouleau et al., 2021).

Opportunities Identified: Areas of Research Potential. The literature review highlights several research opportunities in cotton productivity improvement, some of which vary from region to region. Current studies focus on elements such as the effect of crop rotation, the influence of climate change, the physical and biological properties of the soil, and the effects of cover crops. The results of conservation agriculture systems appear dependent on duration of practices, diversification of the rotation (Thierfelder and Mhlanga, 2022), and limited studies in time and space do not allow a complete and holistic understanding of the impacts of tillage practices. These contrasting responses require in-depth, contextualized analysis, as crop productivity is complex and highly dependent on environmental variables, soil type, crop interventions, and duration of adoption (Singh et al., 2023). The need for long-term research, particularly in Africa, to understand the potential impacts of conservation tillage practices on soil fertility functions such as carbon and nutrient cycling or soil structure in cotton cropping systems is also highlighted (DeLaune et al., 2019). Varietal diversity emerges as a promising solution for weed control, but gaps remain in understanding the interaction between cotton varietal diversity, soil-level functional group dynamics, and cotton yields (Hu et al., 2021; Naeem et al., 2021). The use of herbicide-resistant GM cotton varieties in developed countries associated with conservation tillage or conservation agriculture-based systems highlights the need for further exploration of environmental impacts on soil microflora and biological properties (Blaise et al., 2021). Many transgenic cotton varieties are grown in conservation tillage-based systems, suggesting that the use of herbicide-tolerant varieties facilitates conservation tillage. Yet conventional cotton varieties are still widely grown in sub-Saharan Africa. Research must consider these varieties, and more particularly their agromorphological diversity. In all regions, the integration of economic factors into current studies is often neglected. Understanding the economic impact of different tillage practices is

essential to promote sustainable and profitable practices. Thus, in exploring innovative tillage practices, future research must seize these opportunities to integrate contextual variability, incorporate economic aspects, address field implementation challenges, understand complex interactions with other agricultural practices, and anticipate climate change impacts. A multidisciplinary approach combining agronomy, soil science, crop physiology, and molecular biology are required to address these challenges comprehensively (Nachimuthu and Webb, 2017).

Limitations of this Systematic Review. This literature analysis was essentially limited to articles in the SCOPUS and DIMENSIONS databases, which are indexed journals, to guarantee quality control and scientific credibility. As consequence, few documents from grey literature (documents not traditionally published in scientific journals) were exploited to gain a better understanding of aspects related to the history and diversity of soil practices in cotton-based cropping systems. It was not our objective to analyze the methodological approaches of each article. As such, we have not taken a critical look at the methodologies used in the articles. The number of articles exploited from Africa, South America, and Oceania is small and can be linked to the countries' investment in cotton research on the one hand, and the available databases exploited on the other. Despite these limitations, this work provides important information on the status of tillage practices in cotton-based cropping systems.

CONCLUSION

Sustainable cotton production through the efficient use of diminishing resources and the implementation of best management practices will maximize the productivity and profitability of cotton-based cropping systems. In developed cotton-producing countries, soil conservation practices combined with other technologies, such as transgenic varieties, have improved considerably to ensure higher productivity. The major challenge for these countries is to ensure the sustainability of these technological advances by developing multidimensional approaches supported by research. Soil conservation practices are still under-used in African cotton-growing countries, due to technical and socioeconomic problems, and the productivity of cotton systems remains low. Dedicated research to explore further avenues will

help meet the specific challenges in these regions for design of agroecological and sustainable cotton-based system.

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