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Agrotechniques for millets under conservation agriculture: A review

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Abstract

Millets are widely recognized as climate-resilient nutri-cereals with significant potential to enhance food and nutritional security under conditions of water scarcity and increasing climate variability. Their inherent tolerance to drought and marginal environments makes them well suited to sustainable agricultural systems. Conservation agriculture (CA), based on the principles of minimum soil disturbance, permanent soil cover, and diversified cropping systems, complements the resilience of millets by improving soil quality, conserving natural resources, and enhancing long-term productivity. This review summarizes recent advances in agronomic practices for millet cultivation under conservation agriculture, focusing on tillage and seedbed preparation, sowing time, seed priming, crop geometry, nutrient and microbial management, biochar application, irrigation scheduling, weed management, soil biological health, and cropping system diversification. Recent studies on foxtail, pearl, finger, proso, and browntop millets indicate that zero tillage combined with residue retention, particularly under ridge-and-furrow planting systems, improves crop growth, grain yield, and water-use efficiency compared with conventional tillage. Selecting appropriate sowing windows and region-specific cultivars enhances thermal-unit utilization and overall productivity, while seed priming using chemical, osmotic, or biological agents promotes better germination, vigorous seedling establishment, and improved crop performance. Precision nutrient management, including site-specific fertilizer application, sensor-guided nutrient management, foliar sulphur supplementation, and microbial inoculants, increases nutrient-use efficiency and improves grain nutritional quality. Likewise, integrating maize-straw biochar with conservation practices enhances soil physical properties and contributes to higher millet yields. Residue mulching and efficient irrigation scheduling improve soil moisture conservation, whereas timely weed management minimizes crop-weed competition during the early growth stages. Conservation agriculture also promotes soil biological health by increasing soil organic carbon, microbial biomass, and enzymatic activity compared with conventional cultivation practices. Furthermore, integrating legumes into millet-based cropping systems under zero tillage enhances system productivity while improving grain protein content and micronutrient concentration. Overall, the evidence demonstrates that integrating conservation tillage, residue management, precision nutrient strategies, biological inputs, and diversified cropping systems can substantially improve the productivity, resilience, and sustainability of millet cultivation. Future research should prioritize remote-sensing-based decision-support tools, climate-resilient millet varieties, long-term carbon sequestration studies, and supportive policies to accelerate the adoption of conservation agriculture for sustainable millet production and strengthened global food and nutritional security.

Keywords: Conservation agriculture, millets, zero tillage, residue retention, nutrient management, sustainable agriculture

1. Introduction

Owing to their high nutritional value and ability to perform well under resource-limited and stress-prone environments, millets have recently regained attention as important crops for sustainable agriculture. Their cultivation declined markedly after the Green Revolution of the 1960s, particularly in South Asia, as high-yielding rice and wheat varieties became the dominant staple crops. Recognizing their importance for sustainable agriculture and nutrition, the United Nations declared 2023 as the International Year of Millets to encourage their cultivation and integration into mainstream food systems in support of Sustainable Development Goal 2 (Zero Hunger) ^[1]. Although their protein content is comparable to that of major cereals, millets are

distinguished by their greater concentration of dietary fibre, minerals, calcium, iron and health-promoting compounds such as carotenoids. Their natural absence of gluten also makes them suitable for gluten-sensitive individuals. In addition, they are naturally gluten-free, making them an ideal dietary option for individuals suffering from celiac disease or gluten [1, 2, 5]. Their short crop duration, extensive root system, and tolerance to drought, high temperatures, and intermittent moisture stress enable them to better withstand climatic variability³. Although millets once occupied a significant share of India's agricultural landscape, the Green Revolution shifted production toward high-yielding rice and wheat varieties, restricting millet cultivation largely to marginal and rainfed areas [2, 4] despite the considerable untapped yield potential that exists, particularly under rainfed conditions [2, 3].

Conservation agriculture (CA) promotes sustainable crop production through reduced soil disturbance, continuous soil cover using residues or cover crops, and diversified crop sequences⁶. Because CA enhances resource-use efficiency and strengthens the ability of farming systems to cope with climatic variability without compromising productivity, it is considered an important climate-smart agricultural strategy [7]. Growing concerns over soil degradation, biodiversity loss, and increased greenhouse gas emissions resulting from intensive tillage have accelerated the adoption of CA practices [8]. The long-term goal of CA is to protect soil and natural resources while maintaining productive and economically viable cropping systems⁹. Numerous long-term studies conducted in maize–wheat systems have demonstrated that CA-based sustainable intensification improves crop productivity, profitability, water- and energy-use efficiency, soil organic carbon accumulation, and carbon sequestration potential [10–15]. Residue retention through mulching has been shown to improve soil moisture conservation and weed suppression, leading to grain and straw yield increases of approximately 24.3–36.1% in small millets [16]. Furthermore, integrating millets into diversified cropping systems enhances resilience against both biotic and abiotic stresses while improving dietary diversity, food security, and farmers' livelihoods [17]. Therefore, this review compiles and evaluates recent evidence on agronomic interventions for millet cultivation under conservation agriculture, covering tillage practices, sowing management, seed enhancement techniques, crop geometry, nutrient and microbial approaches, biochar, irrigation, weed management, soil health, and cropping system diversification in order to identify effective strategies and future research needs.

2. Agrotechniques for Millets under Conservation Agriculture

2.1 Tillage and seedbed preparation

Zero tillage is one of the principal components of conservation agriculture, where crops are established without prior land preparation. By minimizing soil disturbance, this practice helps preserve soil structure, protects soil biota, and supports long-term soil functioning. Because millets possess efficient root systems and are well adapted to moisture-deficient environments, they establish successfully even under reduced- or zero-tillage conditions. Reduced soil disturbance under zero tillage improves infiltration and limits moisture loss through evaporation, thereby increasing soil water availability, particularly in semi-arid and arid millet-growing regions [18, 19]. Naidu *et al.*^[20] compared conventional tillage, minimum tillage, zero tillage, and zero tillage with ridge-and-furrow (ZTRF) under different levels of crop residue retention in a

rainfed foxtail millet–greengram system. Retaining the entire crop residue further improved vegetative growth and biomass accumulation compared with residue removal, highlighting the importance of residue management in conservation agriculture [20].

In pearl millet-based production systems, Faiz *et al.*^[21] observed that zero tillage combined with crop residue retention consistently outperformed conventional tillage in terms of productivity and nutrient uptake. Their study compared pearl millet–mungbean, pearl millet–fodder pearl millet, and pearl millet–chickpea rotations under different tillage practices. Among the tillage × cropping system combinations, the pearl millet–mungbean rotation under ZTR recorded the highest grain and stover yields, together with greater nutrient uptake and enhanced micronutrient biofortification. Overall, the results indicate that combining zero tillage with residue retention and legume-inclusive crop rotations can improve productivity while enhancing nutrient uptake and grain micronutrient enrichment in pearl millet systems [17].

2.2 Optimum Sowing Window and Thermal-Unit Utilization

Crop growth, phenological development, biomass production, and yield are strongly influenced by temperature because it determines the accumulation of thermal time throughout the growing season [22]. Therefore, selecting an appropriate sowing window is essential for maximizing millet productivity. To determine the influence of planting time on thermal indices and crop performance, Aishwarya *et al.*^[23] compared different sowing windows during June and July in proso millet, assessing growing degree days (GDD), photothermal units (PTU), heat-use efficiency (HUE), and productivity. The investigation revealed that crops sown during the second fortnight of June achieved significantly greater grain and straw yields, as well as higher economic returns, than those established during either earlier or later sowing periods [23].

Table 1: Effect of different sowing windows on grain yield and economic returns of proso millet

Sowing window	Grain yield (kg ha ⁻¹)	Net returns (Rs ha ⁻¹)
1st fortnight of June	1581.7	33, 165
2nd fortnight of June	2059.3	50, 100
1st fortnight of July	1254.3	21, 602

Source: Aishwarya *et al.*^[23]

In finger millet, Dhavan *et al.*^[24] observed that sowing during the 27th meteorological week (2–8 July) along with the cultivar Phule Nachani promoted superior vegetative growth and productivity, recording greater plant height, tiller production, dry matter accumulation, and grain and straw yields than crops established during later sowing periods. A delay in sowing up to the 33rd meteorological week progressively reduced crop growth and yield attributes, highlighting the importance of timely crop establishment. Saikishore *et al.*^[25] found that browntop millet sown on 15 June and supplied with 60 kg N ha⁻¹ exhibited maximum plant height, leaf area development, dry matter production, improved panicle characteristics, and higher grain and straw yields. Nevertheless, the response obtained with 60 kg N ha⁻¹ did not differ significantly from that recorded with 40 kg N ha⁻¹, indicating that both nitrogen levels produced comparable results [25]. Overall, the available evidence suggests that synchronizing sowing time with favourable environmental conditions, together with the selection of suitable cultivars and appropriate nitrogen management, improves thermal-time utilization, promotes better crop growth, and enhances productivity across diverse millet species.

2.3 Seed treatment and priming

Seed priming involves treating seeds before sowing to improve germination, enhance seedling vigour, and achieve uniform crop establishment, ultimately promoting more efficient utilization of available resources. In proso millet cv. CO₄, Narayanan *et al.*^[26] compared different halo-, osmo-, and bio-priming treatments and identified 2% potassium dihydrogen phosphate (8 h), 2% mannitol (8 h), and 15% *Pseudomonas fluorescens* (8 h) as the most effective treatments within their respective priming categories. Compared with untreated seeds, these priming treatments significantly enhanced seed imbibition, germination percentage, and seedling vigour index^[26].

Bezboruah *et al.*^[27] investigated the performance of three foxtail millet cultivars under different organic nutrient management practices that included vermicompost, beejamrutha-based seed biopriming, and foliar application of panchagavya or jeevamrutha. Among the cultivars tested, SiA-3156 responded most favourably to seed biopriming combined with vermicompost and foliar application of panchagavya, recording earlier seedling emergence, tillering, panicle initiation, flowering, and physiological maturity^[27]. Overall, the results indicate that combining seed biopriming with organic nutrient management practices can improve crop establishment and accelerate phenological development in foxtail millet^[27].

2.4 Plant geometry and fertilizer interaction

Appropriate plant geometry and seed rate are essential for efficient utilization of light, nutrients, and growing space, while their effects on crop performance largely depend on the nutrient supply available to the crop. In a study on foxtail millet, Pawar *et al.*^[28] found that adopting a wider spacing of 60 cm × 10 cm together with the gross recommended dose of fertilizers (GRDF) promoted maximum leaf area development, tillering, and dry matter accumulation. Conversely, taller plants were observed under the narrower planting geometry^[28]. Kumar *et al.*^[29] demonstrated that finger millet grown at a spacing of 30 cm × 30 cm with 125% of the recommended NPK dose achieved superior vegetative growth, exhibiting greater plant height, increased tillering, and higher dry matter production. However, maintaining a closer spacing of 20 cm × 20 cm with the same fertilizer dose resulted in the highest grain yield (3.32 t ha⁻¹) and harvest index, suggesting that the spacing required for optimum vegetative growth may differ from that needed to achieve maximum grain production^[29].

2.5 Nutrient management

Efficient nutrient management is essential for finger millet grown in calcareous soils because high soil pH and low organic carbon levels often limit nutrient availability, thereby reducing crop growth and productivity^[30]. Under such soil conditions, improving nutrient-use efficiency requires site-specific nutrient management (SSNM), which enables fertilizer application to be adjusted according to crop demand³⁰. In finger millet cultivated under calcareous soil conditions, Pramanick *et al.*^[30] evaluated nutrient omission treatments, varying fertilizer recommendations, and a GreenSeeker-based site-specific nutrient management (SSNM) approach. The GreenSeeker-guided SSNM strategy, which integrated basal fertilizer application with nitrogen scheduling based on real-time canopy reflectance, outperformed the other nutrient management practices by producing the highest grain yield, net energy output, and agronomic use efficiencies of nitrogen, phosphorus, and potassium^[30].

Adequate sulphur nutrition plays a significant role in improving

the growth and productivity of pearl millet, particularly under conservation agriculture. Under rainfed zero-tillage conditions with residue retention, Ankit *et al.*^[31] evaluated foliar application of ammonium thiosulphate as a sulphur management strategy in pearl millet. Although the recommended soil application of sulphur at 30 kg ha⁻¹ produced the highest overall crop performance, two foliar sprays of 10% ammonium thiosulphate applied at 30 and 60 days after sowing achieved statistically comparable improvements in growth and yield, increasing grain and stover yields by approximately 19.5% and 13.2%, respectively, compared with the treatment that received no sulphur^[31].

2.6 Microbial inoculants and biofertilization

The use of microbial inoculants alongside chemical or organic fertilizers can improve nutrient availability, enhance crop quality, and strengthen plant tolerance to various environmental stresses^[32]. Studies in small millets have shown that liquid microbial consortia can enhance crop productivity while reducing dependence on conventional fertilizers, making them well suited to the resource-conserving approach of conservation agriculture^[33]. Overall, integrating microbial inoculants into nutrient management strategies offers a promising means of improving nutrient-use efficiency and promoting sustainable millet production within conservation agriculture systems^[23, 33].

2.7 Biochar application

Biochar is a carbon-rich product obtained by the pyrolysis of crop residues and is increasingly being used as a soil amendment because it improves soil physical properties, enhances water retention, facilitates nutrient cycling, and contributes to long-term carbon storage^[34]. In newly reclaimed soil, Hou *et al.*^[35] evaluated the application of maize-straw biochar at 3, 4.5, and 6 t ha⁻¹ before sowing foxtail millet to determine its influence on crop performance and soil properties. Compared with the untreated control, maize-straw biochar increased foxtail millet grain yield by 12–54% over two consecutive cropping seasons^[35]. Biochar treatment also improved soil moisture retention, increased nutrient availability, and stimulated soil enzymatic activity^[35]. The porous nature of biochar and its positive effects on soil quality make it especially suitable for restoring degraded soils. When integrated with practices such as residue retention and reduced tillage, biochar can further strengthen the effectiveness of conservation agriculture systems^[34, 35].

2.8 Irrigation and water management

Compared with major cereal crops, millets require relatively less water for successful cultivation, with total water requirements generally ranging from 35 to 50 cm, depending on the species. Water requirements also vary among millet species, with pearl millet and finger millet having comparatively lower moisture needs than little millet, kodo millet, barnyard millet, and foxtail millet.

Under situations where supplemental irrigation is feasible, applying two to three light irrigations at the pre-flowering, post-flowering, and grain-filling stages is generally sufficient to obtain optimum crop performance. In rainfed production systems, irregular rainfall distribution and prolonged dry spells frequently limit crop growth, emphasizing the importance of conserving soil moisture. In conservation agriculture, maintaining continuous soil cover through crop residues or cover crops is an effective strategy for reducing moisture loss and improving water availability. Sathiya *et al.*^[16] evaluated no tillage, minimum tillage, and mulching in six small millet

species and found that mulching consistently achieved the highest relative water-use efficiency, with the most pronounced improvements observed in foxtail millet and finger millet.

2.9 Weed management

Weed infestation during the initial stages of millet growth restricts crop establishment by competing for moisture, nutrients, light, and space, while some weed species may also act as alternate hosts for insect pests and disease-causing organisms [36]. Therefore, timely weed control is essential to sustain millet productivity and improve the economic viability of millet-based production systems while supporting food security [36]. The duration of the critical crop–weed competition period varies among millet crops, extending from 15–30 days after sowing in pearl millet, 25–42 days in finger millet, and 28–42 days in sorghum. Effective weed management during this period is therefore essential to minimize yield losses [37].

Kauri and Singh [38] investigated the effects of planting geometry, organic mulch levels, and weed management practices in rainfed hybrid pearl millet. Application of organic mulch at 4 t ha⁻¹ reduced weed population and weed dry matter more effectively than 2 t ha⁻¹, demonstrating the advantage of

higher mulch levels for weed suppression [38]. Furthermore, both one hand weeding at 15 days after sowing and pre-emergence application of atrazine effectively suppressed weed growth and increased grain and stover yields compared with the untreated weedy check [38]. Overall, residue-based mulching can serve as an effective component of integrated weed management in conservation agriculture. When necessary, its effectiveness can be further enhanced through timely mechanical or chemical weed-control measures during the critical period of crop–weed competition [38].

2.10 Soil health and enzymatic activity

The biological activity and diversity of soil microorganisms are key determinants of soil health, influencing nutrient cycling, soil water dynamics, and the mitigation of greenhouse gas emissions [39]. Soil enzymes contribute significantly to soil fertility by accelerating organic matter decomposition and facilitating the release of nutrients needed for plant growth. Hasanath *et al.* [41] compared different tillage and crop establishment methods in small millets and observed that minimum tillage recorded the highest soil organic carbon content (2.09%), whereas conventional tillage had the lowest value (1.50%).

Table 2: Effect of tillage practices on soil enzymatic activities in rainfed finger millet

Tillage practice	Urease activity ($\mu\text{g NH}_4\text{-N g}^{-1}\text{ hr}^{-1}$)	Dehydrogenase activity ($\mu\text{g TPF g}^{-1}\text{ 24 hr}^{-1}$)	Acid phosphatase ($\mu\text{g PNP g}^{-1}$)	Alkaline phosphatase ($\mu\text{g PNP g}^{-1}$)
Conventional tillage	18.07	98.28	20.66	25.38
Minimum tillage	23.09	119.74	26.43	29.18
Zero tillage	31.76	183.79	34.34	35.11

Source: Hatti *et al.* [42]

In rainfed finger millet, Hatti *et al.* [42] investigated the combined effects of conservation tillage and nutrient management and found that zero tillage maintained significantly higher soil moisture during dry periods than conventional tillage. Compared with conventional tillage, the zero-tillage system enhanced soil water-holding capacity, increased soil organic carbon, microbial population, microbial biomass carbon, and soil nitrogen status, while also stimulating the activities of urease, dehydrogenase, acid phosphatase, and alkaline phosphatase [42]. The positive effects of zero tillage were further strengthened when nutrient management was supplemented with farmyard manure and horsegram residue mulch. Overall, the findings indicate that combining reduced tillage with residue-based organic nutrient management is an effective strategy for improving soil biological properties and sustaining soil health in millet-based production systems [42].

2.11 Cropping system diversification

The short crop duration and adaptability of millets to diverse environmental conditions make them suitable for various cropping systems, including intercropping, sequential cropping, and relay cropping. Diversifying millet-based production systems with pulses or oilseed crops improves system productivity and soil fertility while contributing to better food and nutritional security and greater resilience to biotic and abiotic stresses [43, 44]. Yogi [45] compared a conventional tillage-based pearl millet–mustard system with several zero-tillage production systems in which cowpea, chickpea, or cluster bean were included as system-intensification components to evaluate the combined effects of tillage, residue management, and cropping system diversification [45]. Zero-tillage systems integrated with legumes consistently outperformed the conventional tillage system by producing higher grain and stover

yields [45]. In addition to increasing productivity, these diversified systems enhanced grain protein and oil content and improved the concentration and uptake of micronutrients, including iron, zinc, manganese, and copper [45]. Residue retention during both the kharif and rabi seasons further increased grain yield and micronutrient accumulation [45]. Overall, the available evidence indicates that combining zero tillage, residue retention, and legume-based cropping system diversification can enhance yield stability while improving the nutritional quality and micronutrient enrichment of pearl millet grains [45].

3. Future Prospects

Future research on conservation agriculture in millet-based production systems should focus on integrating remote sensing technologies, drone-assisted crop monitoring, and decision-support systems to enable site-specific crop management. Greater emphasis should also be placed on developing climate-resilient millet cultivars and integrating them with biofertilizers, biochar, and precision nutrient management to enhance productivity and sustainability, particularly under rainfed conditions. Further diversification of millet-based cropping systems through the inclusion of pulses and oilseed crops has considerable potential to improve soil fertility, nutritional security, and farm income. In addition, long-term investigations are required to assess the contributions of conservation agriculture to soil carbon sequestration and greenhouse gas mitigation, thereby providing a better understanding of its environmental benefits. Achieving large-scale adoption of these practices will depend on supportive policy interventions, effective farmer training and extension programmes, and the development of robust millet value chains.

4. Conclusion

The findings synthesized in this review demonstrate that conservation agriculture provides a sustainable approach to enhancing millet productivity, improving soil health, and increasing resilience to climatic variability. Compared with conventional cultivation practices, the adoption of zero or minimum tillage, crop residue retention, optimum sowing time, seed priming, precision and microbial-based nutrient management, biochar application, mulch-assisted moisture conservation, and legume-based cropping diversification consistently enhances crop growth, grain yield, resource-use efficiency, and grain quality across different millet species. However, realizing these benefits under field conditions will require effective farmer capacity-building programmes, location-specific management recommendations, and supportive policy frameworks. The wider adoption of conservation agriculture in millet cultivation has the potential to establish a resource-efficient, climate-resilient, and environmentally sustainable production system capable of contributing significantly to future food and nutritional security.

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