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A Review on Millet Cultivation in India: Soil, Climate, and Productivity Perspectives

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This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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Abstract

Millets—comprising major millets (sorghum, pearl millet and finger millet) and a diverse set of small millets—are increasingly recognised in India as strategic crops for nutrition-sensitive and climate-resilient agriculture. Yet, despite their ecological hardiness and cultural embeddedness, millet productivity remains constrained by interacting soil limitations, rainfall variability, suboptimal agronomy, and uneven access to improved cultivars and markets. This review synthesises contemporary evidence on the soil, climate and productivity dimensions of millet cultivation in India, with emphasis on rainfed agro-ecosystems where millets predominate. Across regions, millet performance is shaped by inherently low soil organic carbon, widespread macro- and micronutrient deficiencies, and degraded physical structure in marginal lands, often intensified by limited organic inputs and low fertiliser use. Climatic exposure—particularly erratic monsoon onset, extended dry spells, and episodic heat stress—drives large year-to-year yield variability and reinforces risk-averse management. Advances in integrated nutrient management, land and water conservation, and targeted breeding for drought and heat adaptation have demonstrated potential to raise yields while sustaining soil health. This review highlights emerging systems approaches, including millet-based agroforestry and

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diversified rotations, that align livelihood goals with soil restoration and climate adaptation. Finally, policy and institutional developments supporting millet revival are assessed in relation to on-farm constraints, value-chain barriers and evidence needs for equitable scaling.

Keywords: Millets; rainfed agriculture; soil fertility; soil organic carbon; monsoon variability; heat stress; integrated nutrient management; climate adaptation; agroforestry.

1. Introduction

Millets—encompassing major millets such as sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*) and finger millet (*Eleusine coracana*), along with a diverse group of small millets—have long underpinned food and livelihood security across India's drylands and upland farming systems. Their agronomic identity is closely tied to rainfed production, limited access to irrigation, and the capacity to provide grain and biomass under fluctuating weather conditions. In recent years, renewed attention to millets has been propelled by converging priorities: dietary diversification and nutrition, resilience to climatic variability, and the need to re-orient parts of Indian agriculture towards sustainability and risk reduction in water-stressed regions (Sharma et al., 2025). Yet the contemporary resurgence of interest also raises a critical agronomic question: how can millet systems deliver reliable productivity gains on the marginal soils and climate-risk landscapes where they are most commonly cultivated? Millets would play a greater role in future agriculture due to challenges posed by climate change, limited water supply, and reduced agro-biodiversity. This would need a much greater intensity of investment in millet research and adequate support as extended to wheat and rice. Increased emphasis on their genetic improvement and agronomic management is required to develop cultivars, using new tools and technologies, with high production potential and adequate environmental adaptation to make millets competitive with other crops (Yadav et al., 2024; Sawargaonkar et al., 2025).

Millets are frequently described as "climate-resilient" crops, but resilience is often misunderstood as an assurance of high yields. In practice, resilience in millet-based systems typically reflects a higher probability of obtaining at least some harvest under adverse conditions, rather than consistently high grain output. This distinction matters in India because much millet cultivation occurs in environments characterised by low and erratic rainfall, high evaporative demand, and soils that are inherently constrained or degraded. In such contexts, farmers often adopt risk-averse management—reduced input use, minimal fertiliser application, and limited soil amendments—not because millets do not respond to improvements, but because the probability of pay-off is uncertain when rainfall distribution is unpredictable. Consequently, productivity remains constrained not only by climate exposure but also by soil fertility depletion, weak soil structure, and limited investment in agronomic intensification. Recent synthesis focused on India highlights that nutrient management practices and broader policy and institutional factors together shape yield outcomes and farm incentives, underscoring that agronomic solutions must be embedded within enabling environments (Warisa et al., 2025). Despite their high nutritional value and classification as a"superfood,"the global cultivation area for millets has steadily declined. This reduction can be attributed to the Green Revolution, which prioritized major cereal crops, thereby limiting the expansion of millet production. However, in response to contemporary global challenges, including climate change, water scarcity, undernutrition, and population growth, millets are regaining attention for their potential role in sustainable agriculture (Muskan et al., 2025).

A soil–climate–productivity lens is therefore essential for understanding millet cultivation in India beyond generic narratives. Soil properties determine the extent to which rainfall is converted into plant-available water, the rooting depth and rooting efficiency of millet crops, and the capacity of soils to supply nutrients during critical growth stages. Climatic regimes govern not only the total seasonal water available but also the timing of wet and dry spells, heat events, and the length of the effective growing period. Productivity outcomes, in turn, emerge from how well crop genetics and management align with these soil–climate realities. The interplay is particularly important in semi-arid tropics and arid zones where a short sequence of rainfall events can establish the crop, while subsequent dry spells or terminal stress may decide grain set and final yield. Evidence from India-based work integrating field experimentation and simulation has shown that relatively practical agronomic choices—such as land configuration and sowing time adjustments—can measurably alter soil water dynamics and reduce yield penalties under rainfall variability, reinforcing that adaptation is neither automatic nor purely varietal (Kamdi et al., 2023).

At a broader scale, the sustainability argument for millets depends substantially on productivity and stability. Low-input production does not necessarily equate to low impact per unit of output; when yields are low, environmental burdens per kilogram of grain can remain unfavourable even if total input use is modest. Life-cycle sustainability assessment of crops in India indicates that agricultural environmental performance must be interpreted in relation to output, implying that strengthening millet productivity and yield stability is central to improving efficiency and sustainability simultaneously (Selvaraj et al., 2021). This is consistent with the wider framing that millets can contribute to sustainable agriculture and diverse food systems, but only if constraints that suppress yields—soil fertility limitations, management gaps, and climatic risks—are addressed in a coordinated manner (Sharma et al., 2025).

India's millet revival is also deeply connected to institutions and markets. The decline of millet cultivation in several regions was not solely agronomic; it was shaped by shifts in dietary patterns, procurement and price incentives, processing bottlenecks, and the relative profitability of alternative crops. Conversely, re-strengthening millet cultivation requires that productivity improvements translate into tangible livelihood benefits. Lessons from long-term, community-centred interventions in South India suggest that rebuilding a millet economy is feasible when production support is coupled with efforts that strengthen consumption and local value chains, and when institutions persist long enough to overcome structural constraints (Nithya et al., 2025). These insights matter for the soil and climate discussion because farmers' willingness to invest in soil fertility restoration, improved seed and better agronomy is closely linked to expectations of market stability, price realisation and reduced downside risk.

From an agronomic perspective, millets are not a monolith. Species differ in phenology, rooting patterns, sensitivity to heat during flowering, and responsiveness to nutrients under variable moisture. Equally, India's millet ecologies vary widely—from coarse-textured soils with low water-holding capacity in arid belts to deeper, heavier soils in parts of the semi-arid tropics. The practical outcome is that both constraints and solutions are highly context-specific. A climate-smart framing of millets has argued that these crops can play a strategic role in future farming systems, but only if research and development prioritise the alignment of genetic improvement with management strategies and production environments (Bandyopadhyay et al., 2017). In Indian rainfed agriculture, this alignment often hinges on interventions that jointly improve soil water capture and retention, enhance nutrient supply through balanced and integrated inputs, and stabilise yields against rainfall and temperature fluctuations.

1.1 Millets in India's Rainfed Agro-Ecologies

Millets are concentrated in rainfed and resource-constrained regions where production is shaped by monsoon variability, limited irrigation access and a predominance of low-to-moderate fertility soils. In such systems, farmers commonly value millets for their reliability relative to some alternative crops, their biomass contribution to livestock, and their ability to fit within diversified cropping patterns. However, the same environments that favour millets also impose large yield variability. Addressing productivity therefore requires interventions that reduce sensitivity to dry spells and improve the efficiency with which limited rainfall and soil nutrients are translated into grain and fodder (Kamdi et al., 2023; Warisa et al., 2025).

1.2 Why a Soil–Climate–Productivity Framing Matters Now

Current momentum around millets, including sustainability and nutrition narratives, creates an opportunity to shift millet cultivation from a low-input, low-yield equilibrium towards a more stable and rewarding trajectory. Yet this transition must be realistic for rainfed conditions: it should strengthen soil health and water productivity, while ensuring that farmers can capture value through supportive markets and institutions. Evidence suggests that achieving these outcomes will require coordinated progress in agronomy, sustainability-oriented system design, and the strengthening of local millet economies (Nithya et al., 2025; Selvaraj et al., 2021; Sharma et al., 2025; Warisa et al., 2025).

1.3 Scope and Objective of the Article

This review examines millet cultivation in India through an explicitly integrated lens that connects soil constraints, climatic drivers, and productivity outcomes. The scope covers major millets and, where evidence is available, representative small millets cultivated across India's rainfed and semi-arid agro-ecologies, with particular emphasis on the production environments where millets remain most important for smallholder livelihoods and mixed crop–livestock systems. The review considers how soil physical condition (such as structure, depth and water-holding capacity), soil fertility status (including macronutrient and micronutrient limitations), and soil biological functioning jointly influence crop establishment, stress tolerance and yield stability under variable monsoon behaviour and temperature regimes. It also evaluates how management interventions—including nutrient strategies, land and water conservation practices, and cultivar selection—shape both grain and biomass productivity, as well as longer-term soil health trajectories that determine the sustainability of intensification.

The objectives are threefold. First, the article synthesises the principal soil and climatic constraints that limit millet yields and amplify risk in Indian production landscapes, highlighting the mechanisms through which these constraints operate. Second, it critically assesses agronomic and system-level pathways that can narrow yield gaps and improve yield reliability without undermining soil quality, with attention to practical feasibility under resource-limited conditions. Third, it identifies priority evidence needs and research directions to support scalable, regionally appropriate improvement of millet-based systems, spanning diagnosis, management design, varietal targeting and the alignment of on-farm strategies with broader sustainability goals. Consistent with these aims, the review focuses on peer-reviewed evidence and interprets productivity in a systems context, recognising that the success of millet cultivation is measured not only by grain yield but also by stability, profitability, and the capacity to sustain production on challenging soils under a changing climate.

2. Methods for Literature Selection

A focused literature search was conducted using Web of Science, Scopus and Google Scholar. The search window prioritised publications from January 2000 through February 2026, with emphasis on 2015–2026 to capture recent agronomic, soil and climate studies. Search strings combined crop and geography terms with soil- and climate-related keywords, for example: “millet* AND India AND soil fertility”, “pearl millet AND drought AND India”, “finger millet AND Alfisol* AND nutrient management”, “sorghum AND rainfed AND sowing time AND India”, and “millet* AND policy AND India”. Studies were included if they (i) examined millets grown in India or presented India-relevant evidence, and (ii) reported soil, climate, management or productivity outcomes. Exclusion criteria included non-scholarly reports, purely descriptive pieces lacking methodological clarity, and studies without stable bibliographic identifiers. Additional relevant articles were identified through backward citation tracking from high-quality reviews and key empirical papers.

3. Soil Perspectives: Constraints and Management Pathways

Millet cultivation in India is strongly shaped by the soils on which it is practised. Although millets are often promoted as crops suited to “marginal” lands, the soil environment is not merely a passive backdrop; it actively determines how rainfall is converted into plant-available water, how efficiently roots explore the profile, and whether nutrient uptake can support reliable grain formation. In many millet-growing belts, the dominant production context is rainfed agriculture with modest external inputs, which means that soil limitations accumulate over time and become central drivers of yield variability. A synthesis of millet cultivation in India underscores that nutrient management and soil-related constraints are inseparable from the observed productivity patterns, particularly where policy incentives and farm resource constraints encourage low-input strategies (Warisa et al., 2025).

Across diverse agro-ecologies, several recurring soil constraints can be identified. Low soil organic carbon is widespread, especially where crop residues are removed for fodder, grazing pressure is high, and manure availability is limited. This depletion reduces aggregate stability, increases surface crusting risk, lowers infiltration, and ultimately weakens the soil’s buffering capacity during intra-seasonal dry spells. In practical terms, poor structure reduces the effectiveness of rainfall by increasing runoff and limiting rooting depth; it also constrains the yield response to fertiliser because nutrient supply cannot compensate for restricted root growth and moisture stress. Nutrient deficiencies—especially nitrogen and phosphorus—are common in millet fields and are often compounded by low cation exchange capacity in coarse-textured soils or by chemical constraints in certain soil types. These constraints are not uniform; rather, they vary with soil class, landscape position, management history, and the intensity of cropping. Yet, the common outcome is that millet crops frequently operate under multi-nutrient limitation, in which addressing one deficiency without improving the broader soil condition yields only partial benefits.

The management pathway most consistently highlighted in the Indian millet literature is integrated nutrient management, which seeks to combine mineral fertilisers with organic resources to improve both immediate nutrient supply and longer-term soil function. Warisa et al. (2025) emphasise that balanced nutrient practices are essential if millet systems are to deliver productivity gains in a manner that is agronomically robust and scalable. The rationale is straightforward: mineral fertilisers provide precise and timely nutrient delivery, while organic inputs contribute carbon, improve physical condition, stimulate biological activity, and support nutrient retention. However, the availability of organic resources is often constrained by competing uses—especially livestock feed and fuel—and by labour requirements. This makes integrated approaches particularly relevant because they can be designed around realistic quantities of organics while still addressing the core nutrient gaps through judicious fertiliser use (Warisa et al., 2025).

3.1 Building Soil Organic Matter and Restoring Nutrient-Supplying Capacity

Empirical evidence from finger millet-based systems shows that sustained organic additions can improve soil quality and support stable productivity over time. Long-term work under a finger millet–groundnut system in southern India demonstrated that combining organic manures with manufactured fertilisers improved soil quality indicators and sustained finger millet productivity, illustrating the long horizon over which soil restoration benefits become visible (Satish et al., 2016). Such findings are important for millet regions because soil organic matter restoration is inherently cumulative: meaningful improvement in structure, infiltration, and nutrient cycling often requires repeated additions and consistent management rather than one-off applications.

Complementary long-term evidence from a dry zone of Karnataka indicates that integrated nutrient management can maintain or improve soil nutrient status and plant nutrient uptake in finger millet, suggesting that repeated integrated inputs can strengthen the soil's capacity to supply nutrients across seasons (Prashanth et al., 2019). This matters because one key reason farmers in risk-prone environments underapply fertiliser is the uncertainty of response. By improving soil condition and nutrient retention, integrated approaches can gradually increase the reliability of crop response, thereby reducing perceived risk and improving the economic rationale for modest intensification.

3.2 Micronutrients and the Hidden Constraint in Millet Productivity

Micronutrient limitations can depress millet yields and grain quality even when macronutrients are supplied. Long-term application of farmyard manure has been shown to influence soil micronutrient status, implying that organic amendments can play a role in sustaining micronutrient availability alongside improvements in organic matter and structure (Chaudhary & Narwal, 2005). Evidence also suggests that organic manures and fertilisers together can improve the status of soil organic matter and nutrients more broadly, which is relevant because micronutrient dynamics are strongly affected by organic matter, soil pH, and adsorption processes (Antil & Singh, 2007). In practice, this implies that micronutrient management for millets should not be treated as an isolated add-on; it is often most effective when embedded within integrated nutrient strategies that build organic matter and support balanced fertility.

3.3 Short-to-Medium Term Yield Gains Through Realistic Integration of Organics

While long-term studies demonstrate trajectory change, farmers also need near-term yield benefits to justify adoption. A two-year rainfed study on Alfisols in southern India found that integrating organics into nutrient management for finger millet improved yield and enhanced soil organic carbon and available nutrients, reinforcing the principle that soil fertility improvement and productivity gains can be aligned even within relatively short time horizons when integration is designed appropriately (Prabhakar et al., 2023). This type of evidence is particularly relevant for millet-based livelihoods because Alfisols and other structurally fragile soils are common in millet zones; improving their organic carbon status can strengthen water availability during dry spells and improve nutrient uptake efficiency, thereby stabilising yields.

3.4 Soil Management and Sustainability: Productivity as a Prerequisite for Efficiency

Soil restoration pathways in millet systems have wider sustainability implications, but these depend strongly on productivity outcomes. A life-cycle sustainability assessment across Indian crops highlights that environmental performance is closely tied to yield, implying that improving productivity and stability can reduce impact intensity per unit of output (Selvaraj et al., 2021). This is a critical point for millets, because low input use does not automatically translate into favourable environmental outcomes if yields remain very low. Soil-focused interventions that build organic matter and improve nutrient efficiency can therefore support both farm resilience and environmental efficiency by raising yield while limiting avoidable losses.

In sum, the soil perspective suggests that millet productivity in India is constrained less by any single factor than by interacting limitations—organic matter depletion, nutrient imbalances (including micronutrients), and physical degradation. The most credible management pathways are those that raise the soil's water and nutrient buffering capacity while remaining feasible for rainfed smallholders. Evidence from integrated nutrient management and organic–mineral combinations indicates that such pathways can improve yields and soil fertility simultaneously, but they require persistence and enabling conditions that support farmer investment and learning (Antil & Singh, 2007; Chaudhary & Narwal, 2005; Prabhakar et al., 2023; Prashanth et al., 2019; Satish et al., 2016; Warisa et al., 2025).

4. Climate Perspectives: Rainfall Variability, Heat Stress and Adaptation

Millet cultivation in India is fundamentally climate-facing because it is concentrated in rainfed regions where crop performance is governed not only by seasonal rainfall totals but, more critically, by rainfall distribution, dry-spell frequency and the timing of heat exposure. The ecological reputation of millets as hardy cereals stems from their ability to complete a life cycle under moisture limitation and to provide at least some harvest under conditions that frequently suppress more water-demanding crops. Yet, in practice, "resilience" does not imply climatic immunity. Millet yields can fluctuate sharply from year to year because Indian monsoon behaviour is inherently variable, and because the most common millet environments combine rainfall uncertainty with high evaporative demand. This produces a recurring pattern: relatively brief windows of favourable moisture after monsoon onset may establish the crop, but subsequent dry spells and terminal stress often determine whether that early vegetative growth is translated into grain.

Rainfall variability affects millets at multiple scales. At the onset of the monsoon, delayed or staggered rains can compress sowing windows, forcing farmers to sow under suboptimal soil moisture or to shift to shorter-duration varieties. Even when seasonal totals are adequate, intra-seasonal breaks can create early stress that compromises tillering and leaf area development, weakening the crop's capacity for later recovery. Conversely, intense rainfall events separated by longer dry periods may generate runoff and poor infiltration in degraded fields, leaving crops water-stressed despite apparently "good" rainfall years. These dynamics underscore why climate adaptation in millets must be framed as management of rainfall *patterns* rather than simple averages, and why soil water capture and retention are tightly coupled with climate outcomes even though the stress signal originates from weather.

Heat stress is an increasingly visible risk in several millet regions, particularly when high temperatures coincide with flowering and grain filling. Physiologically, millets can tolerate high temperatures better than many cereals, but reproductive processes remain sensitive. Hot, dry winds and elevated vapour pressure deficit can accelerate phenology, reduce pollen viability and impair grain set in susceptible genotypes. Under rainfed conditions, heat stress is often compounded by moisture stress, creating a "double constraint" in which the plant cannot cool effectively through transpiration and simultaneously faces reduced assimilate supply due to stomatal closure. These combined stresses are particularly damaging when they occur during the transition from vegetative growth to reproduction, because the crop's earlier ability to survive drought does not guarantee successful grain formation.

Pearl millet provides a useful reference point for understanding drought adaptation under Indian conditions because its cultivated range includes some of the harshest arid and semi-arid environments. Importantly, drought tolerance is not a single trait; it is an outcome of water acquisition, water use regulation and reproductive resilience. Physiological evidence indicates that water-conserving behaviour expressed even under well-watered conditions—specifically, traits that restrict transpiration—can be correlated with improved terminal drought tolerance in pearl millet, suggesting a mechanism that helps conserve soil moisture for later reproductive stages (Kholová et al., 2010). In practical terms, such traits matter in Indian monsoon systems where early rains can promote rapid vegetative growth, yet terminal drought remains common. A genotype that conserves water earlier may reduce the probability of catastrophic reproductive failure later, even if the trade-off is slightly lower early biomass under non-stress conditions.

From a breeding and deployment perspective, the central challenge is that drought and heat are not uniform across India's millet zones; stress timing differs among locations and seasons. A breeding-oriented synthesis emphasises that progress depends on combining conventional selection with genomic approaches while explicitly recognising the diversity of drought patterns and target environments (Srivastava et al., 2022). This has practical implications for India: breeding pipelines and varietal testing need to represent the range of stress scenarios farmers face—early-season drought, intermittent dry spells, and terminal stress—rather than relying on a single generic drought screen. It also strengthens the case for location-specific varietal targeting, because a cultivar that performs well in one rainfall regime may underperform in another if phenology and stress exposure are mismatched.

Management adaptation can complement breeding and, in certain cases, deliver benefits more rapidly. Evidence combining field experiments and simulation in the semi-arid tropics of India indicates that relatively accessible agronomic adjustments—such as altering land configuration to improve rainwater capture and adjusting sowing timing—can influence soil moisture availability and reduce yield losses under climate variability for sorghum-based systems (Kamdi et al., 2023). The significance of this result is not limited to sorghum; it illustrates a broader principle for millets in India: adaptation is often achieved through modest changes that improve the synchrony between rainfall occurrence and crop water demand. Land configurations that reduce runoff and improve infiltration can be especially valuable when rainfall arrives in high-intensity bursts, while sowing time management can help avoid the coincidence of reproductive stages with the most likely periods of heat and moisture stress.

Looking beyond current variability, climate-change-oriented assessments point to the value of explicitly breeding for combined heat and drought tolerance in pearl millet. Modelling-based evaluation for arid and semi-arid locations in India suggests that genetic improvements targeting heat and drought tolerance can generate yield gains under projected climate conditions, though benefits are expected to vary across locations because the direction and magnitude of climatic change are not uniform (Singh et al., 2017). The practical inference is that "future-proofing" millet production will require a portfolio approach: multiple cultivars with complementary adaptation profiles, combined with management packages that reduce exposure to stress at sensitive stages.

Small millets add an additional adaptation dimension because their cultivation is frequently associated with heterogeneous microclimates, uplands and tribal regions where locally adapted landraces persist. In such settings, the conservation of genetic diversity is itself a resilience strategy, preserving traits that align with niche soil and climate combinations and supporting production stability in variable years. Evidence on the ecological stability of genetic diversity among little millet landraces in south India underscores the relevance of maintaining landrace diversity for adaptation and future improvement (Arunachalam et al., 2005). This is particularly important where formal seed systems are weak and where climatic variability interacts with complex terrain to produce highly localised stress environments.

Overall, the climate perspective indicates that millet resilience in India is best understood as a function of exposure management and trait–environment matching, rather than as an inherent guarantee of stable yields. Rainfall variability, heat stress and their interaction can suppress grain formation even when crops establish well. Effective adaptation therefore combines (i) genetics that regulate water use and protect reproduction under stress (Kholová et al., 2010; Srivastava et al., 2022), (ii) agronomy that improves the timing and efficiency of rainwater use (Kamdi et al., 2023), and (iii) the conservation and deployment of locally adapted diversity, particularly for small millets cultivated in heterogeneous environments (Arunachalam et al., 2005). Under climate change, location-specific breeding and management portfolios are likely to be decisive for sustaining and improving millet productivity across India's dryland landscapes (Singh et al., 2017).

5. Productivity Perspectives: Genetics, Agronomy and Yield Gaps

Productivity in India's millet systems emerges from the interaction of genetic potential, agronomic management and the degree to which soil and climatic constraints are mitigated at field level. In many regions, millets are cultivated in environments where rainfall uncertainty and low soil fertility encourage risk-averse decision-making. This context is important because it helps explain why realised yields can remain modest even when improved varieties and better management are available. The resulting yield gaps are not simply technical; they reflect the economics of risk under rainfed agriculture, the opportunity costs of labour, and the extent to which markets reward higher grain quality and consistent supply. Consequently, strategies to raise millet productivity must be credible under variable rainfall, compatible with smallholder resource constraints, and sufficiently profitable to justify investment.

5.1 Genetic Improvement and Cultivar Targeting in India

India has a long history of millet genetic improvement, particularly for pearl millet. Breeding programmes have delivered hybrids and improved varieties that combine higher yield potential with adaptation to dry environments, and they have increasingly targeted traits relevant to nutritional quality and stress resilience. A detailed overview of the genetic improvement of pearl millet in India highlights the breadth of progress in breeding and the continuing importance of cultivar development for both productivity and food security, while also recognising that gains depend on effective deployment into diverse target environments (Yadav & Rai, 2013). From a productivity perspective, the key point is that genetic improvement expands the attainable yield frontier, but farm-level benefits depend on matching cultivar phenology and stress response to local rainfall patterns and soil conditions.

Even within the same millet species, performance can differ sharply across locations because stress exposure varies in timing and intensity. Multi-location evaluation across arid and semi-arid regions of India has demonstrated strong genotype-by-environment interaction for pearl millet grain yield and micronutrient traits, indicating that stability and adaptation are not incidental but central to cultivar recommendation (Sanjana Reddy et al., 2021). This matters for closing yield gaps because it implies that “one-size-fits-all” varietal promotion may dilute gains: a cultivar that performs well in one rainfall regime or soil type may underperform elsewhere, not because its potential is low, but because its stress sensitivities are mismatched to local conditions. The productivity payoff from breeding, therefore, increases when varietal testing networks represent the diversity of Indian millet ecologies and when seed systems can deliver the right cultivar to the right place.

5.2 Agronomy, Nutrient Response and the Reality of Rainfed Risk

Yield gaps in millets are frequently reinforced by suboptimal agronomy. Poor stand establishment, delayed weeding, inadequate nutrient supply and weak soil moisture management can each reduce yields; together they often lock farmers into a low-input equilibrium. However, the response of millets to agronomic intensification is highly conditional on moisture. Where rainfall distribution is favourable, balanced nutrition and timely management can raise yields substantially; where terminal drought or long dry spells occur, yield responses can be muted and the risk of input loss becomes a major deterrent. Thus, the central productivity challenge is to design interventions that improve yield stability and reduce the probability of “failed response”, thereby making investment rational in risk-prone settings.

Evidence from rainfed Alfisols in southern India shows that integrating organic inputs within nutrient management can improve finger millet yield while simultaneously enhancing soil organic carbon and available nutrients, suggesting a pathway that can strengthen both short-term output and the underlying resource base (Prabhakar et al., 2023). From a productivity lens, this is important because improved soil organic carbon and nutrient availability can make yield responses more reliable across seasons by improving rooting conditions, water buffering and nutrient supply synchrony. In effect, such strategies can convert some portion of climatic risk into manageable agronomic variation, thereby narrowing yield gaps over time.

5.3 Yield Stability, Quality Traits and Adoption Incentives

For many farmers, stability matters as much as mean yield. In rainfed landscapes, a variety that delivers moderate yield with high reliability may be preferred over one that offers high yield only in favourable years. The evidence of significant genotype-by-environment interaction in pearl millet, including for micronutrients, reinforces that breeding and dissemination should explicitly consider stability profiles across stress environments rather than focusing solely on peak yield (Sanjana Reddy et al., 2021). This also links to markets and nutrition: if procurement and consumer demand reward grain quality and micronutrient attributes, farmers may have stronger incentives to adopt improved varieties and invest in management, provided that yield stability is not compromised. Conversely, when markets are uncertain or processing bottlenecks exist, farmers may prioritise dual-purpose traits such as biomass yield and fodder value, again placing stability at the centre of cultivar choice.

5.4 Measuring Productivity in a Systems Context

Millet productivity is often under-assessed when analysis focuses only on grain yield per hectare. In many Indian millet systems, biomass production is economically and nutritionally important through livestock integration, and crop residues can contribute to household resilience during drought years. Productivity perspectives must therefore account for how agronomy and cultivar choice affect both grain and stover outputs, as well as how residue management interacts with soil fertility trajectories. Approaches that raise total biomass can, in some cases, make partial residue retention more feasible without undermining fodder supply, which in turn supports soil organic matter restoration and future yield stability. While this section focuses on productivity mechanisms, the broader implication is that closing yield gaps will often require integrated strategies that jointly support grain output, fodder needs and soil health, rather than treating these goals as competing priorities.

5.5 Productivity, Sustainability and Efficiency Considerations

Environmental performance is increasingly relevant to discussions of millet scaling, but it is tightly bound to productivity. Life-cycle sustainability assessment of crops in India indicates that impact profiles depend strongly on yield, suggesting that improving millet productivity and stability is essential to reducing environmental burdens per unit of output, even where inputs are relatively low (Selvaraj et al., 2021). This provides a useful corrective to simplistic narratives: low input use does not automatically ensure high sustainability if yields remain very low. From a policy and development perspective, it implies that agronomic and genetic improvements that close yield gaps can support sustainability outcomes, provided they do not trigger disproportionate increases in resource use or emissions.

In sum, productivity enhancement in India’s millet systems requires simultaneous attention to genetics, agronomy and risk. Genetic improvement has expanded yield potential and adaptation options, but effective cultivar targeting and stability assessment remain pivotal for heterogeneous environments (Yadav & Rai, 2013; Sanjana Reddy et al., 2021). Agronomic intensification can raise yields, yet it must be designed to reduce downside risk and strengthen the soil resource base, as illustrated by integrated nutrient management benefits in finger millet (Prabhakar et al., 2023). Finally, closing yield gaps is inseparable from the broader sustainability and efficiency context in which millets are promoted, because productivity gains underpin both livelihood viability and environmental performance (Selvaraj et al., 2021).

6. Systems and Sustainability Perspectives: Diversified Pathways for Scaling

Millet cultivation in India is rarely a single-crop enterprise in the strict sense; it is more often embedded within diversified farming systems designed to manage rainfall risk, stabilise food supply, and meet multiple household needs across the season. A systems perspective is therefore essential when discussing sustainability and scaling, because the performance of millets depends not only on varietal choice and field-level management but also on how millets are integrated with other crops, trees, livestock, labour calendars, and local markets. This integration influences resource use efficiency, resilience to climatic shocks, and the overall value that farmers can capture from millet cultivation. At the same time, contemporary arguments for expanding millets as “sustainable” and “climate-resilient” crops require careful interpretation: the sustainability of millet-based pathways is realised through how systems are configured and supported, rather than being guaranteed by the crop species alone (Sharma et al., 2025).

A key feature of millet-based systems is their functional diversity. Millets are often grown in rotations or mixtures because farmers seek to spread risk across rainfall scenarios and to avoid total crop failure in bad monsoon years. Diversification can operate through temporal sequencing (rotations that distribute peak water and nutrient demands across seasons) and through spatial mixing (intercropping and mixed stands). Such arrangements can reduce vulnerability by ensuring that at least one component performs reasonably under a given stress pattern, and they can improve resource capture by utilising different rooting habits and canopy structures. From a sustainability standpoint, diversified millet systems can also support soil cover and reduce erosion during intense rainfall events, while crop mixtures can buffer weed pressure and, in some contexts, reduce reliance on external inputs. Yet diversification should not be romanticised as universally beneficial: poorly designed mixtures can intensify competition for scarce moisture, and labour constraints can make complex systems difficult to manage at scale. The practical implication is that scaling millets sustainably requires not only agronomic recommendations but also attention to labour-saving practices, locally appropriate crop combinations, and an understanding of how farmers prioritise grain, fodder and cash needs across variable years.

The sustainability narrative also depends on how millets connect to diets and demand. In India, millets are increasingly promoted for nutritional value and culinary diversity, with implications for market creation and value addition. Such demand-side changes can influence sustainability indirectly by altering farm incentives: where there is reliable demand and price realisation, farmers are more likely to invest in yield-stabilising practices and post-harvest quality management. Conversely, where processing and marketing bottlenecks persist, farmers may treat millets primarily as subsistence or fodder-linked crops, limiting investment and slowing productivity growth. Evidence synthesising the role of millets as nutrient-rich, climate-resilient crops emphasises that realising their promise involves overcoming practical constraints in production and post-harvest systems and strengthening pathways for broader utilisation (Sharma et al., 2025). In this sense, “sustainable scaling” is not only an agronomic project but also a system transition that links production environments to processing capacity and consumer acceptance.

6.1 Millet-Based Agroforestry and Landscape Integration

One diversified pathway receiving growing attention is the integration of millets into agroforestry and tree-based systems, especially in rainfed landscapes where soil degradation, heat stress and livelihood vulnerability co-occur. Agroforestry can alter the microclimate experienced by the crop, improve soil structure and organic matter over time through litter inputs, and diversify household income sources via tree products. These potential advantages are particularly relevant in India’s dryland regions, where tree components can provide stability when annual crop yields fluctuate. However, agroforestry is not automatically beneficial; tree–crop interactions can shift from facilitative to competitive depending on tree density, species choice, rooting patterns and rainfall regime. The challenge, therefore, is to design millet–tree configurations that improve soil health and resilience without imposing unacceptable yield penalties or labour burdens.

A recent synthesis focusing on India highlights agroforestry as a climate-smart strategy for integrating millets into sustainable land-use systems, while also noting that successful design requires attention to local ecology, farmer objectives and management feasibility (Das et al., 2025). This emphasis is important for scaling: agroforestry is a long-term investment, and adoption is more likely when farmers can anticipate multiple benefits—soil improvement, fodder availability, risk buffering, and supplementary income—rather than a single yield-focused outcome. From a systems standpoint, agroforestry can be viewed as a landscape-level complement to field-based soil and water management, strengthening resilience by improving the overall resource base within which millet cultivation operates.

6.2 Environmental Performance, Efficiency and the Centrality of Productivity

Discussions of sustainability increasingly seek quantifiable evidence on environmental performance. Life-cycle approaches are particularly informative because they evaluate impacts relative to outputs, helping to clarify a common misunderstanding: low-input cultivation does not necessarily imply low impact per unit of grain if yields are very low. A life cycle sustainability assessment of crops in India indicates that environmental performance can be strongly influenced by productivity, implying that yield stability and moderate intensification can improve impact efficiency, provided that input increases are judicious and losses are minimised (Selvaraj et al., 2021). For millet scaling, this means that sustainability strategies should prioritise the reduction of avoidable inefficiencies—such as poor nutrient use efficiency, post-harvest losses, and low-value marketing—rather than focusing solely on minimising inputs.

This framing also draws attention to the role of post-harvest systems. Processing, storage and transport can influence overall environmental footprints as well as farmer incomes. Where decentralised processing reduces losses and adds value locally, it can improve both livelihood outcomes and the efficiency with which land and water resources are translated into usable food. In addition, dietary diversification towards millets—supported by improved processing and culinary innovation—can influence sustainability by reshaping demand and encouraging more resilient cropping patterns in water-stressed regions (Sharma et al., 2025). The core argument is that sustainable scaling of millets is achieved through a chain of improvements: stable field-level production, efficient post-harvest handling, and markets that reward quality and reliability.

Overall, diversified pathways for scaling millets in India are best understood as integrated system choices rather than single interventions. Agroforestry integration offers a long-term route to resilience and land restoration when designed for local conditions (Das et al., 2025). Environmental performance depends on productivity and efficiency across the value chain, not simply on low input use (Selvaraj et al., 2021). Finally, sustainability narratives are strengthened when production improvements connect to utilisation, processing and dietary acceptance, ensuring that farmers benefit from the transition (Sharma et al., 2025).

7. Policy and Institutional Dimensions: Enabling Conditions for Productivity and Soil Health

Millet productivity in India is not determined by agronomy alone. Even where improved varieties, soil-restoring nutrient strategies, and moisture-conserving practices are technically feasible, farmers' decisions to adopt them depend heavily on policy signals and institutional support. This is particularly true in rainfed regions, where seasonal risk is high and where farmers often prioritise strategies that reduce the chance of loss rather than those that maximise yield in favourable years. In such contexts, policies and institutions shape whether investment in soil fertility restoration, improved seed, and better crop management appears rational and worthwhile. A recent synthesis emphasises that the geography of millet cultivation, patterns of nutrient management, and the broader policy environment are tightly linked, implying that productivity gains require coherence between technical recommendations and enabling conditions on the ground (Warisa et al., 2025).

A central institutional constraint historically associated with millets has been weak market assurance relative to other staples. When farmers lack confidence that higher production will translate into stable prices and timely sales, they remain reluctant to increase input use or adopt practices whose benefits accrue gradually, such as building soil organic matter. Conversely, when markets are reliable—through procurement, organised local demand, or functioning value chains—farmers are more likely to consider incremental intensification and longer-term soil health investments. The policy implication is that "millet promotion" cannot be restricted to area expansion targets; it must address the incentive environment that determines whether productivity-enhancing and soil-improving practices are adopted at scale (Warisa et al., 2025).

7.1 From Crop Revival Narratives to Practical Incentive Structures

Policy narratives increasingly frame millets as climate-resilient and nutrition-relevant crops, yet farm-level change depends on practical incentive structures. If farmers perceive millets as low-value crops with uncertain offtake, they may continue cultivating them mainly for household needs or fodder, with minimal cash investment. This tends to lock millet production into a low-input equilibrium that suppresses yields and can accelerate soil degradation through limited nutrient return and residue removal. By contrast, if policies help stabilise demand and improve price realisation—whether through public programmes, institutional consumption, or strengthened local markets—farmers may be more willing to adopt yield-stabilising practices and to allocate better land and labour to millet cultivation. Warisa et al. (2025) highlight that nutrient management and productivity trajectories are shaped not only by technical knowledge but also by the policy environment that influences what farmers can afford and what they expect to gain.

7.2 Institutional Linkages between Production Support and Soil Health

Soil health improvement in millet landscapes is intrinsically a medium- to long-term process. It typically requires repeated application of organic resources where available, balanced fertilisation, and better field management that improves infiltration and reduces erosion. Such changes are difficult to sustain without institutional mechanisms that provide continuity—extension follow-up, access to inputs, and locally relevant advice that adapts recommendations to rainfall and soil variability. Where institutions are intermittent, farmers may experiment briefly but abandon practices if benefits are not immediate or if they encounter a bad rainfall year. Therefore, enabling soil health for millet productivity is as much an institutional challenge as an agronomic one.

In this respect, the most instructive examples often involve long-running, community-centred approaches rather than short project cycles. Lessons from a South Indian case study show that strengthening a millet economy required sustained engagement that linked biodiversity and production with consumption and local value chains, rather than treating these as separate domains (Nithya et al., 2025). The relevance for soil health is direct: when local demand and value are reinforced, farmers have stronger incentives to invest in practices that improve productivity and maintain soil function over time. Without such incentive alignment, soil health recommendations may remain technically sound but practically marginal.

7.3 Seed Systems, Extension Capacity, and the "Last-Mile" Problem

Even when improved millet cultivars exist, scaling their benefits depends on seed availability, farmer trust, and guidance on how to manage them under local constraints. Institutional capacity matters here in two ways. First, seed systems must deliver cultivars suited to local rainfall and soils, and not merely make seed available in aggregate. Second, extension systems must translate varietal and management guidance into local decision-making—when to sow under uncertain monsoon onset, how to adjust nutrient application under variable rainfall, and how to manage weeds and crop stands when labour is constrained.

The "last-mile" problem is particularly acute for millets because production environments are heterogeneous and risk-sensitive. Farmers may be reluctant to adopt a new cultivar if they cannot obtain seed reliably for subsequent seasons, or if they fear that a variety will fail under a drought pattern typical of their location. Institutional mechanisms that provide multi-season support, facilitate farmer-to-farmer learning, and stabilise access to inputs can therefore be decisive. Warisa et al. (2025) reinforce that agronomic improvement in millet cultivation is inseparable from the institutional and policy context that shapes adoption feasibility and continuity.

7.4 Processing, Local Value Chains, and the Economics of Intensification

Millets often face constraints beyond the farm gate, and these constraints strongly condition whether farmers perceive productivity enhancement and soil restoration as worthwhile investments. Processing capacity, aggregation channels, and the predictability of marketing arrangements influence not only price realisation but also farmers' willingness to invest in improved seed, balanced nutrition, and management practices whose benefits are partly delayed through soil health improvement (Warisa et al., 2025). Where processing and market infrastructure are weak or fragmented, farmers may continue to treat millets as subsistence or fodder-linked crops managed with minimal cash inputs, reinforcing a low-input equilibrium that keeps yields and quality gains below attainable levels.

Recent work on value addition highlights how processing innovation can strengthen demand-side pull for millets and thereby improve the incentive environment for farmers. For example, a narrative synthesis on germination-based transformation of finger millet emphasises that germination can enhance functional and sensory attributes and support the development of value-added products, which is relevant because stronger consumer acceptability and product diversification can stabilise demand and improve price prospects for producers (Vanshika et al., 2025). In practice, such demand-side strengthening becomes most meaningful when paired with reliable local processing and procurement arrangements that reduce transaction uncertainty and reward quality.

Evidence from technology demonstrations in Karnataka also shows how institutional and market frictions can shape adoption outcomes even when productivity gains are agronomically achievable. In a study assessing adoption of finger millet production technologies, constraints reported by farmers extended from production issues (such as labour availability and seed access) to market constraints including price fluctuation and institutional procurement/payment delays, illustrating how downstream uncertainty can dampen incentives for input use and quality-oriented management (Srinivas et al., 2024). Economic evidence from rainfed pearl millet production similarly indicates that profitability constraints are not purely agronomic but are mediated by output prices and input cost structures; in such contexts, farmers may be unwilling to commit to repeated soil-improving investments unless returns become more predictable (Sreedhar et al., 2021). These linkages matter because soil-health practices typically require continuity over seasons, and discontinuous adoption is common when market and institutional risks dominate farmer calculations (Warisa et al., 2025).

Accordingly, strengthening millet value chains should be viewed as a productivity and soil-health intervention in its own right. Lessons from South India suggest that rebuilding millet cultivation is more feasible when production support is coupled with sustained institutional engagement that also strengthens consumption and local value chains, thereby improving the likelihood that farmers can capture value from improved production and quality (Nithya et al., 2025). When decentralised processing, stronger procurement discipline, and predictable local marketing arrangements reduce downside risk, they make incremental intensification more attractive—creating the enabling conditions under which soil-restoring practices can be adopted and maintained over time (Nithya et al., 2025; Warisa et al., 2025).

8. Future Research Directions

Future progress in millet cultivation in India will likely depend on integrating soil restoration with climate adaptation and targeted productivity enhancement. Research priorities include improving diagnostic understanding of soil constraints in millet zones, especially micronutrient deficiencies and soil physical limitations that restrict yield response; designing locally adapted nutrient and residue strategies that account for livestock feed needs; and strengthening cultivar targeting through better characterisation of stress patterns and genotype-by-environment interactions. Breeding efforts that combine stress tolerance with nutrient responsiveness and grain quality will be most impactful when aligned with practical agronomy packages for rainfed conditions (Srivastava et al., 2022; Prabhakar et al., 2023). Systems research on millet-based agroforestry and diversified cropping should move from general promise to zone-specific design principles, including planting densities and input regimes that improve soil health without adding unmanageable labour burdens (Das et al., 2025). Finally, policy research should focus on evidence pathways—how procurement, processing infrastructure, and institutional support affect farmers' willingness and ability to invest in soil-improving practices and improved cultivars over time (Warisa et al., 2025; Nithya et al., 2025).

9. Conclusions

Millet cultivation in India cannot be adequately understood through a single narrative of "climate resilience". Productivity outcomes emerge from the interaction of rainfall variability with soil constraints, management intensity and cultivar choice. Across millet-growing regions, low soil organic carbon, nutrient deficiencies and weak soil structure frequently limit yield and amplify climate risk, making soil restoration a central pathway for improving yield stability. Integrated nutrient management and soil water conservation practices demonstrate strong potential to raise yields while enhancing soil properties, particularly in rainfed systems. Genetic improvement has delivered important gains, yet the value of improved cultivars depends on effective targeting to local soil–rainfall environments and on management packages that farmers can adopt under risk. Sustainable scaling of millets will therefore require coordinated advances across agronomy, soil health strategies, breeding, and enabling institutions that create reliable market incentives for farmers.

10. Limitations

This review is constrained by the uneven distribution of high-resolution agronomic evidence across millet species and regions in India, with comparatively stronger coverage for major millets than for several small millets. Differences in study designs, soil classifications, and climate descriptors across the literature also limit direct comparability of reported yield responses and soil changes. Finally, because on-farm adoption is shaped by local labour, livestock and market conditions, agronomic outcomes observed in research-managed trials may not fully represent performance under heterogeneous smallholder realities.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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