

Performance of Foxtail Millet Varieties Under Varying Row Spacing in Semi-Arid Alfisols

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ABSTRACT

Foxtail millet (Setaria italica) is a short-duration, drought-tolerant cereal that suits the rainfed Alfisols of the semi-arid tropics, and row spacing is one of the cheapest agronomic levers available to the farmers who grow it. Recommendations for spacing are nonetheless inconsistent, and varieties are often advised the same geometry regardless of their architecture. This narrative review asks what the published literature can and cannot say about the performance of foxtail millet varieties under different row spacings on semi-arid Alfisols, and it reports no new data. It draws on work on the biology and tillering of foxtail millet, on the physics of water and radiation capture in sparse canopies, on the long-standing theory of plant population and yield, and on the statistics of genotype-by-environment trials. The central difficulty is that the best spacing is not a property of the crop alone: it shifts with variety, with the amount and timing of rainfall, and with soil fertility, while most field trials come from a single site and a single season and so confound these influences. Wide rows tend to favour stored water and tillering where rain is scarce, and narrow rows favour early canopy closure and weed suppression where it is not, but the crossover point is poorly characterised. The review closes with the design features that a convincing multi-season, multi-site spacing trial would need.

Keywords: Foxtail millet; *Setaria italica*; Row spacing; Plant density; Semi-arid Alfisols; Genotype by environment; Narrative review

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1. Introduction

Foxtail millet is one of the oldest cereals in cultivation, with a long history in the dry farming systems of northern China [1], and it remains a crop of rainfed Asia today. It matures quickly, it asks little of the soil, and it is among the crops that farmers turn to when the rains are late or uncertain [2, 3]. Its grain is valued as food, and its nutritional profile has drawn renewed attention [4]. Yet for all that history, the agronomy of the crop is thinly documented compared with that of

the major cereals.

Row spacing is a good example. Moving the rows closer together or further apart costs a farmer nothing in purchased inputs, yet it changes how the crop shares light, water and nutrients with itself and with weeds. On the red, shallow and crust-prone Alfisols that dominate much of the Indian semi-arid tropics, where rain falls in a few events and then stops, the geometry of the crop can matter more than it would on a deep, well-watered soil [5, 6]. Advice nonetheless tends

to arrive as a single number for the crop as a whole.

This review asks what the published literature can say about how foxtail millet varieties perform under different row spacings in semi-arid Alfisols, and how far any answer can be trusted. The difficulty is that the best spacing is not a property of the crop alone. It depends on the variety, on the rainfall of the season and on the fertility of the field, and most trials are run at one site for one season, so these influences are tangled together. We set out the biology, the physical reasoning and the statistical limits that bear on the question, and we end with what a convincing trial would need to contain. The aim is a fair account of what is known and what is merely repeated.

The article is a narrative review. It reports no new data, and where the foxtail millet literature is silent we say so, borrowing reasoning from closely related cereals rather than quoting yield figures we have not been able to check against their sources.

2. Literature Review

2.1 Foxtail Millet as a Crop

Foxtail millet, *Setaria italica*, is a C4 grass, and the efficiency of that photosynthetic pathway in warm, bright conditions is a large part of its appeal in dry regions [7]. The crop has also become a model for the study of grass genetics, with a sequenced genome and a close wild relative [8, 9], and reviews of that work stress its small genome, short life cycle and inbreeding habit [3, 10]. These advances have given breeders tools, but they have not been matched by an equally rich body of field agronomy.

What the field work needs is an account of how plants behave in a stand, and here the most useful biology concerns architecture. Foxtail millet and its wild relative differ in how readily they branch, and branching responds to both genotype and environment [11]. Grasses vary widely in the number, timing and fate of their tillers, and domestication has often reshaped that pattern [12]. A variety that tillers freely can fill space on its own, while a variety with one dominant stem relies on neighbours to close the canopy. Row spacing and variety are therefore not independent choices.

2.2 Semi-Arid Alfisols and the Water Problem

Alfisols in the semi-arid tropics are commonly coarse in the surface layer, low in organic matter and limited in the water they can hold, and they tend to seal at the surface after rain. Crops on

them depend on a small number of rainfall events, and a large share of the water that falls may be lost as runoff or evaporation rather than used for growth [5, 13]. The farmers who work them are also working with soils that are short of more than nitrogen: deficiencies of sulphur, boron and zinc have been widely documented across Indian semi-arid soils [14].

The consequence for spacing is that water supply is the first consideration. Yield in a dry environment is often understood as the product of the water a crop transpires, the efficiency with which it turns that water into dry matter, and the share of the dry matter that ends up in grain [13, 15]. Water-use efficiency in the narrow sense is a fairly conservative property of a crop species [16]. What a farmer can change is how much of the available water passes through the crop rather than off the soil surface, and when in the season it is used.

A crop that closes its canopy fast uses water quickly, which helps if the rains continue and hurts if they do not, and it has been argued that traits favouring yield in good seasons and in bad ones are not always compatible [17]. Work on pearl millet, the other great small-seeded cereal of dry regions, treats yield under stress as the outcome of several interacting components [18, 19]. A crop that has had a few weeks of kind weather behaves differently from one that has not.

2.3 Plant Population and Yield: The Old Theory

The relationship between plant population and yield was worked out decades ago and still frames the discussion. Over a wide range, yield per plant falls as plants are crowded, while yield per unit area first rises and then levels off or declines [20, 21]. A review of the quantitative relationships described how the shape depends on the crop and the environment, and how the apparent optimum shifts with growing conditions [22]. The upshot for our question is that the same population can be arranged as narrow rows with plants spaced widely within the row, or as wide rows with plants crowded within it.

Row width and population are not the same variable, although trials often change them together. A change in yield attributed to row spacing may simply be a change in the number of plants per hectare, and the reverse. Separating the two requires holding population fixed while the row width varies, which many experiments do not do. Where they do not, the result is not about geometry at all, and its interpretation is correspondingly weaker. Table 1 summarises the

main sources of variation that complicate advice on spacing.

Table 1. Why row spacing is hard to recommend for foxtail millet on semi-arid Alfisols.

Source of variation	How it alters the best spacing	Consequence for advice
Variety architecture	Tillering and canopy habit differ, so plant-to-plant competition differs [11, 12]	Advice may not transfer between varieties
Rainfall amount and timing	Dry seasons reward stored water; wet seasons reward early cover [6, 13]	Optimum moves between years
Soil fertility	Nutrient supply sets how many plants a field can feed [31, 32]	Depends on fertiliser practice
Weed pressure	Faster canopy closure suppresses weeds [29, 30]	Favours narrow rows where weeds dominate
Surface soil condition	Crusting and runoff alter emergence and infiltration on Alfisols [5, 13]	Stand establishment may override geometry

Note: Qualitative summary of the sources of variation discussed in the text; no figures are given because they depend on site and season.

Crop growth in the absence of stress is closely tied to the amount of light the canopy intercepts and uses [23, 24]. Narrow rows, by making the first leaf area more evenly distributed, can intercept more of the early light, an effect that is greatest when the canopy is slow to develop. Once the canopy has closed, differences in geometry matter less for light, but they may continue to matter for how water is used. Ideotype thinking in breeding has long argued that the best plant type depends on whether the crop is grown at low or high density [25].

2.4 Tillering, Shade and Competition Within the Stand

Plants sense their neighbours through the quality of the light they receive, and crowding triggers a set of responses collectively called shade avoidance, including elongation and a reduction in branching [26]. In cereals, the cessation of tillering has been linked to light interception and to the red to far-red ratio in the canopy [27]. In sorghum, a close relative of the millets, the number of tillers that emerge and survive follows a consistent hierarchy that changes with population density [28].

These findings suggest that a stand of foxtail millet at wide spacing will keep more of its tillers, and a stand at narrow spacing will shed more. Whether the extra tillers contribute to grain depends on whether they set panicles before the water runs

out. Late tillers on a dry soil can be a cost rather than a benefit, because they draw on water and produce little. The balance between early-formed and late-formed tillers is thus one of the least certain parts of the spacing story. This is why the same variety can look excellent in one report and unremarkable in the next.

2.5 Weeds, Fertility and the Rest of the Management Package

Weeds are a central reason farmers care about row width. A crop that closes its canopy early leaves less room and light for weeds, and ecological accounts of weed management list quick canopy closure among the main cultural controls [29]. Models of crop loss from weed competition emphasise how much depends on the relative size and timing of crop and weed [30]. A small-seeded crop that starts slowly is especially exposed, which favours narrow rows where weeds are the main problem, and wide rows where they can be removed between the rows.

Fertility enters in a similar way. A field can only support as many plants as its nutrient supply will feed, and the efficiency with which cereals use applied nitrogen is notoriously modest and variable [31, 32]. On soils that lack micronutrients as well as nitrogen, a spacing trial run without fertiliser may reveal a nutrient constraint instead of a geometry effect [14]. For this reason a statement of the fertiliser applied is as important to the interpretation of a spacing trial as the spacing itself.

3. Materials and Methods

3.1 Scope and Question

The review addresses one question in several parts: how is the performance of foxtail millet varieties expected to change with row spacing on semi-arid Alfisols, and how well does the published evidence pin that change down? We divided it into the sub-questions a spacing trial would have to answer: which varieties were compared, how the spacing and population were separated, what the season and soil delivered, how fertility and weeds were handled, and how the results were analysed.

3.2 Literature Assembly

The review draws on peer-reviewed work in four areas: the biology and genetics of foxtail millet and its relatives; the physiology of water use and radiation capture in dry-land cereals; the classical literature on plant population, tillering and competition; and the statistical literature on variety trials. Sources were chosen for relevance, citation in the field and the clarity of their

methods.

We did not run a formal systematic search and we do not claim one. This is a narrative synthesis, and the choice of sources reflects the authors' judgement. The practical consequence is that the review is a better guide to what a good spacing trial should contain than to the size of any reported effect, and it avoids quoting yields from individual foxtail millet trials that could not be checked against the primary papers for this article.

3.3 Appraisal Framework

To judge how far a report can be trusted, we used a short set of questions. Was row width separated from population [20, 22]? Did the trial span more than one season and more than one site, so that rainfall and soil could be distinguished from spacing [33, 34]? Were varieties described well enough to explain any interaction [35]? Were plots replicated at the level at which the treatment was applied [36]? And were the weeds, fertiliser and sowing date reported? Table 2 lists the mechanisms we asked each report to speak to.

Table 2. Mechanisms through which narrow and wide rows may act on a millet crop.

Mechanism	Narrow rows	Wide rows
Radiation capture	Earlier canopy closure [23, 24]	Later closure, more light lost early
Soil water use	Faster early use; less left for grain filling [15, 16]	Slower use; more held for later growth
Tillering	Suppressed by shade signals [26, 27]	Tillers survive and contribute
Weed suppression	Stronger [29]	Weaker; inter-row weeding possible
Plant-to-plant spacing	More even within the row [22]	Crowded within the row, open between rows

Note: Directions are expectations from the cited physiological literature, not results from foxtail millet trials.

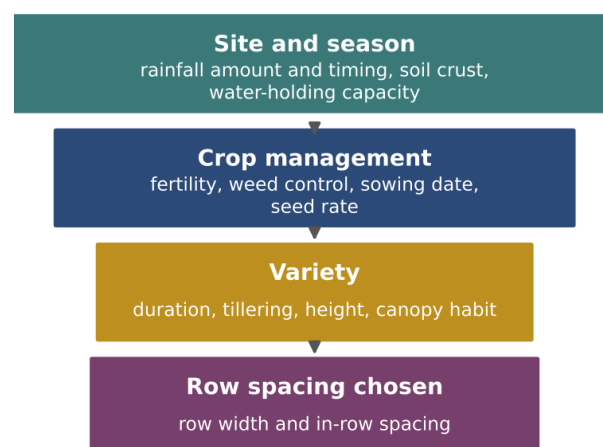
4. Results

4.1 How Spacing Acts on a Millet Crop

Reading across the physiological sources, narrow and wide rows are expected to act through a small set of mechanisms (Table 2). Narrow rows intercept more early light [23, 24], suppress weeds more quickly [29], and spread plants more evenly within the row [22]. Wide rows tend to leave more water in the soil for later in the season [15], allow tillers to survive [26, 27], and make inter-row cultivation practicable. The two sets of effects are not symmetrical in time: the narrow-row advantages arrive early, while the wide-row

advantages arrive late.

Figure 1 sets out the layers of influence that sit between the farmer's choice of row width and the crop that results. The choice is made at sowing, before the season is known, and it acts on a crop whose own architecture varies by variety. Anyone who recommends a spacing is therefore recommending it conditional on a season they cannot yet see, and the recommendation is only as good as the guess about rainfall. Such differences look small in any one season, but they decide whether a recommendation travels.



Each layer conditions the one below it (schematic, not data)

Figure 1. Factors that move the best row spacing, arranged as layers (schematic, not data).

4.2 Where Rainfall Changes the Answer

Because the benefits of narrow rows come early and those of wide rows come late, the best spacing is expected to move with the water supply (Figure 2). In a dry season, a crop that has spent its water by flowering may fail in grain filling, and an arrangement that spares water for later is attractive [13, 16]. In a kind season the early advantages of narrow rows are not paid for later, and the extra light capture and weed suppression can show up as yield. The figure is a schematic of that expectation, not a plot of data, and the location of the crossover is the very quantity the literature does not supply.

There is an uncomfortable consequence. If the crossover lies within the range of seasons a farmer actually sees, then neither spacing wins consistently, and a trial that happens to run in a wet year will favour one answer where a trial in a dry year will favour the other. Both would be correct for their year. Variable rainfall of this kind is a defining feature of rainfed farming [5, 6], and a recommendation that ignores it will fail in some years however well it was tested in others.

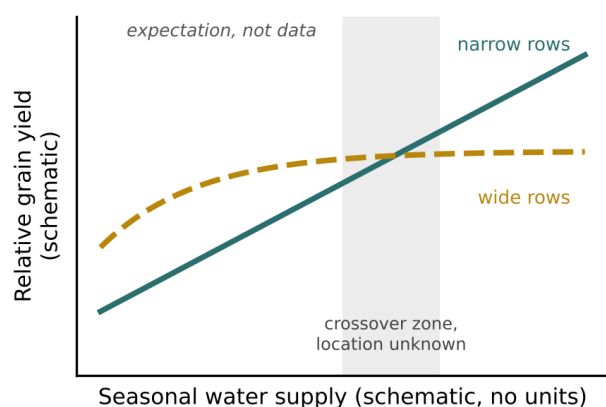


Figure 2. Expected crossover between wide and narrow rows along a rainfall gradient (schematic, not data).

4.3 Genotype by Spacing Interaction

Varieties are not interchangeable. Tillering habit, duration and height all differ, and the reasoning above implies that a variety that tillers strongly can compensate for wider rows and one that does not cannot [11, 12]. Plant breeders have long recognised that the best plant type depends on the density at which it is grown [25], and the components that make up yield differ in how plastic they are across environments [35]. There is also a trade-off between how many seeds a plant sets and how large they are [37], which links spacing to grain size as well as grain number.

Figure 3 sketches the qualitative pattern we would expect for varieties of contrasting tillering habit in dry and wet seasons. It is a set of hypotheses, not findings. It is worth stating that it cannot be filled in from the literature on foxtail millet alone, because the necessary trials, with several varieties of known habit at several spacings across both kinds of season, are rare. The statistical tools to analyse them exist [34, 38, 39]; the field data to which they would be applied largely do not.

	Dry season	Wet season
Strong tillering variety	Wide rows may be enough; tillers compensate	Tillers add shade; narrower rows may help weeds
Weak tillering variety	Gaps cannot be filled; stored water is the issue	Narrow rows likely to capture light early

Hypotheses to test, not results; no data are plotted

Figure 3. Qualitative matrix of how a spacing response may depend on variety type and season (schematic, not data).

4.4 Quality of the Evidence

Reports on spacing in small millets commonly share a set of design limitations (Table 3). Most are from one site and one season, which is the main reason the interaction with rainfall cannot be separated out [33, 34]. Stability analyses of varieties across environments depend on having environments to analyse [38, 39], and a single environment cannot supply them. Spacing and population are often changed together [20, 22], and varieties are named but not characterised, so a reader cannot tell why they differed [35].

Replication is another recurrent problem. Plots placed side by side in one field are sometimes treated as independent when the treatment was applied to the whole field, an error that inflates apparent precision [36]. Reports that give only yield also hide the mechanism: without yield components, water use and weed biomass, an effect of spacing cannot be attributed to light, water or weeds [37]. These problems are shared with much of applied agronomy, and foxtail millet is not unusual in having them; they matter here because the case for any spacing recommendation rests almost entirely on this kind of study. The point is not that a trial is poor, only that its result travels less far than its abstract suggests.

Table 3. Common weaknesses of spacing trials and what follows from them.

Weakness	Consequence	Remedy
Single site	Site effects mistaken for spacing effects [33, 34]	Several sites representing the soil
Single season	Rainfall of one year taken as typical [38, 39]	Repeat across wet and dry years
Spacing and density confounded	Cannot tell geometry from population [20, 22]	Vary row width at fixed population
Varieties not characterised	Interaction unexplained [35]	Record duration, tillering, height
Plots not independent	Overstated precision [36]	Replicate at the field level
Yield only	Mechanism hidden [37]	Record components, water, weeds

Note: Weaknesses are those discussed in the cited methodological literature; they are not attributed to any single study.

Put plainly, the literature supports only a cautious statement. The reasoning from physiology and from related cereals is coherent, and it points to an advantage for wider rows where water is the limit and for narrower rows where light and weeds are. The size of any effect in foxtail millet on semi-arid Alfisols is not established by evidence we can cite with confidence, and the best summary is

that the optimum is variety-dependent, season-dependent and likely to be broad, so that moderate departures from it cost little. That is a modest claim, and it is the one the evidence will currently bear.

4.5 Reading a Claim About Spacing

Tolerance to a poor choice also matters. If the response of yield to row width is flat near its optimum, as the theory of plant population suggests for many crops [20, 22], then a farmer who picks a moderate spacing loses little in either kind of season. A recommendation framed as a robust range is more honest, and more useful, than a single number. It also fits the way risk is managed on small rainfed holdings, where avoiding a bad year often counts for more than winning a good one [2].

5. Discussion

5.1 Interpretation and Practical Reading

The main finding of this review is a conditional one. Wider rows are likely to help where stored water decides the outcome, and narrower rows where early cover and weed control do, and the boundary between the two depends on variety and season. That fits what is known about plant population and yield in general [20, 22], and it implies that the question for a farmer is not what the best spacing is but what the season and the variety are likely to do.

The second conditional concerns fertility. Where nutrients are scarce, the number of plants a field can support is capped, and spacing will matter less than the nutrient constraint [31, 32]. Alfisols with documented micronutrient deficiencies [14] may show no spacing response at all until those deficiencies are addressed. A recommendation on geometry that is detached from fertility practice is incomplete.

A third point concerns the roots, which are almost invisible in the spacing literature. Water acquisition depends on where roots go as well as on the canopy above them, and ideotypes that explore deeper soil have been proposed for other cereals [40]. Whether row width changes rooting in foxtail millet on Alfisols is, to our knowledge, not established. These points apply with equal force to any small millet, not only to foxtail millet.

5.2 Limitations

This is a narrative review and shares the limitations of that form. The selection of sources reflects judgement, no formal search or quality scoring was done, and the review does not quote yields from individual foxtail millet trials, because

these could not be checked against the primary reports for this article. A reader who needs an effect size should consult the original studies directly, applying the appraisal questions above, or wait for a formal systematic review. Reviews of this kind are more useful when they say where the evidence stops than when they smooth it over.

The review also draws on evidence from other cereals, notably sorghum, wheat and pearl millet, which are imperfect proxies for foxtail millet. Their tillering behaviour, canopy structure and water use differ in detail from those of *Setaria*, and we have used them to frame hypotheses rather than to supply answers. The conclusions should be read in that light.

5.3 Implications for Trial Design

A trial that could settle the question would run for several seasons at more than one site on the soil of interest, so that rainfall and place can be separated from spacing [33, 34]. It would hold population constant while row width varies, and it would include varieties of known and contrasting tillering habit, described well enough to explain any interaction [11, 35]. Fertiliser, sowing date and weed control would be reported, and plots would be replicated at the level at which treatments are applied [36].

Measurements should go beyond grain yield. Records of light interception, soil water through the season, weed biomass, tiller number and fate, and yield components would let the mechanism be identified [23, 37]. Analysis should treat the genotype by environment interaction as a result to be explained, using tools built for the purpose [34, 38]. These requirements are demanding, but they are what separates a result a farmer can use from one that only supports a hunch.

5.4 Directions for Future Work

Three needs stand out. First, a formal systematic review of spacing trials in small millets with a transparent search and quality appraisal. Second, well-designed multi-site, multi-season trials of foxtail millet on Alfisols that vary row width at fixed population, with contrasting varieties. Third, work on roots and soil water under different geometries, which would turn the present reasoning into measured fact [15, 40].

6. Conclusion

Foxtail millet is a plausible candidate for careful spacing management on semi-arid Alfisols, and the physiological reasoning for expecting wider rows to help in dry seasons and narrower rows to help in kind ones is coherent. What the literature does

not yet establish is how large the effects are, where the crossover lies, or how far varieties differ. Readers should treat any single recommended spacing with caution until it has been tested across seasons, sites and varieties.

For the practitioner the message is practical rather than discouraging. A moderate spacing is a sensible default, fertility and weeds deserve attention in their own right, and a small, recorded comparison in the farmer's own field can say more than a leaflet. For the researcher, the opportunity is a set of properly designed trials that turn a plausible set of expectations into a measured result smallholders can rely on.

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9. Conflict of Interest

The authors declare no conflict of interest.

10. Author Contributions

A.B. conceived the review and wrote the sections on climate, water and soils. M.M. wrote the sections on crop management and weeds. D.M. wrote the sections on crop physiology and trial design. All authors revised the manuscript and approved the final version.

11. Ethics Statement

This is a review of published literature. No human participants or animals were involved and no ethical approval was required.

12. Data Availability

No new data were generated. All sources are cited in the reference list.

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