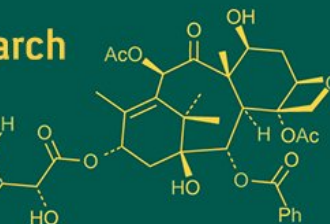
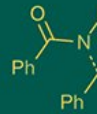


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Wanjiku AM

Senior Lecturer, Department
 of Agricultural Economics and
 Rural Development, Nairobi
 Metropolitan University,
 Nairobi, Kenya

Role of foxtail millet (*Setaria italica*) in enhancing food security among smallholder farming communities

Wanjiku AM

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Abstract

Foxtail millet (*Setaria italica* L.) is among the oldest domesticated cereal crops with demonstrated adaptation to marginal agricultural environments, yet its contribution to household food security among smallholder farming communities remains insufficiently documented. This research assessed the role of foxtail millet cultivation in enhancing multiple dimensions of food security availability, access, utilization, stability, dietary diversity, and income generation among 384 smallholder farming households in four sub-counties of the semi-arid eastern lowlands of Kenya. A cross-sectional survey design employing structured questionnaires, focus group discussions, and key informant interviews was utilized, supplemented by agronomic performance data from on-farm demonstration trials conducted during the 2023 growing seasons. Adopter households (n = 196) were compared with non-adopter households (n = 188) using propensity score matching to control for selection bias. Results demonstrated that foxtail millet adopters scored significantly higher (p < 0.01) across all six food security dimensions, with the largest differentials observed in dietary diversity (4.3 versus 2.3 on a 5-point scale) and food availability (4.2 versus 2.8). On-farm yield trials confirmed average grain yields of 1,840 kg ha⁻¹ under minimal input conditions, with a benefit-cost ratio of 2.8, demonstrating economic viability. The principal adoption constraints identified were limited seed availability (78.4% of respondents), inadequate market access (72.1%), and insufficient processing infrastructure (68.6%). These findings establish foxtail millet as a significant contributor to multi-dimensional food security enhancement and recommend targeted policy interventions addressing identified adoption barriers to accelerate integration into smallholder farming systems across semi-arid East Africa.

Keywords: Food security, foxtail millet, *Setaria italica*, smallholder farming, dietary diversity, adoption barriers, semi-arid agriculture, household nutrition, income generation, crop diversification

Introduction

Foxtail millet has sustained human civilizations for over 8,000 years, with archaeological evidence from the Yellow River valley in China documenting its domestication as one of the earliest cultivated cereal crops in human agricultural history ^[1]. This remarkable historical legacy reflects the species' exceptional adaptability to diverse environmental conditions, its capacity to produce nutritious grain under minimal input management, and its resilience to the climatic stresses that characterize marginal agricultural landscapes. Despite this distinguished pedigree, foxtail millet (*Setaria italica* L.) has experienced progressive marginalization in modern agricultural systems, displaced by high-yielding improved varieties of rice, wheat, and maize that dominate contemporary cereal production and food policy frameworks ^[2, 3].

In sub-Saharan Africa, where approximately 239 million people face chronic food insecurity and climate change is projected to reduce cereal yields by 20 to 30 percent by 2050, the revival and strategic integration of neglected and underutilized crop species offers a pragmatic pathway for strengthening the resilience of smallholder food systems ^[4, 5]. Foxtail millet possesses several attributes uniquely suited to addressing food security challenges in semi-arid environments: drought tolerance enabling production under 300 to 500 mm annual rainfall, a short growing season of 60 to 90 days reducing exposure to terminal drought risk, exceptional nutritional density including elevated protein content (11 to 14 percent) and balanced essential amino acid profiles, and minimal susceptibility to storage pests due to its small grain size and hard pericarp ^[6, 7].

Corresponding Author:**Wanjiku AM**

Senior Lecturer, Department
 of Agricultural Economics and
 Rural Development, Nairobi
 Metropolitan University,
 Nairobi, Kenya

Food security, as conceptualized by the Food and Agriculture Organization, encompasses four fundamental pillars: availability (sufficient quantities of food), access (adequate resources to obtain food), utilization (sufficient nutritional intake and absorption), and stability (consistent access over time) ^[8]. Contemporary frameworks increasingly incorporate dietary diversity and income generation as complementary dimensions that capture the qualitative and economic aspects of food security beyond simple caloric adequacy ^[9]. However, empirical assessments of how the adoption of specific neglected crop species influences these multiple food security dimensions at the household level remain scarce, creating an evidence gap that hinders informed policy advocacy for crop diversification strategies ^[10].

Previous research on millet contributions to food security has predominantly focused on pearl millet and finger millet in West and East African contexts, with limited attention devoted to foxtail millet despite its recognized nutritional superiority and broader agronomic adaptability ^[11]. Furthermore, existing investigations have typically examined single food security dimensions in isolation rather than adopting the multi-dimensional analytical framework necessary to capture the comprehensive livelihood impacts of crop diversification ^[12]. This research addressed these gaps by assessing the influence of foxtail millet adoption on six food security dimensions among smallholder farming households in semi-arid Kenya, evaluating the agronomic and economic performance of foxtail millet under smallholder production conditions, and identifying the principal constraints limiting widespread adoption to inform targeted policy and extension interventions ^[13].

The integration of neglected and underutilized cereal species into existing farming systems requires not only agronomic validation but also comprehensive socioeconomic assessment that captures the multifaceted pathways through which crop diversification influences household welfare outcomes. In the Kenyan semi-arid context, where approximately 3.4 million people face chronic food insecurity exacerbated by recurrent drought events and declining soil fertility, the identification of crop species capable of providing simultaneous nutritional, economic, and ecological benefits represents a critical research priority. Foxtail millet, with its documented adaptability to marginal environments and superior nutritional profile, has been promoted by several East African research institutions, yet rigorous evidence quantifying its actual contribution to household-level food security outcomes has been lacking, limiting the evidence base available to policymakers considering resource allocation for crop diversification programs ^[14, 15].

Materials and Methods

Material

The research was conducted in four sub-counties (Mwingi Central, Mwingi West, Kitui Central, and Kitui South) located in the semi-arid eastern lowlands of Kenya (latitude 0.5° to 1.5°S, longitude 37.5° to 38.5°E), characterized by bimodal rainfall distribution averaging 500 to 750 mm annually with high inter-annual variability. The region is classified as agro-ecological zone IV-V, predominantly supporting mixed crop-livestock farming systems among smallholder households cultivating average farm sizes of 2 to 5 hectares. The sampling frame comprised all farming

households in the four sub-counties, from which 384 households (196 foxtail millet adopters and 188 non-adopters) were selected using multi-stage stratified random sampling proportional to population size. Foxtail millet adoption was defined as continuous cultivation of foxtail millet for at least two consecutive growing seasons preceding the survey. Concurrent agronomic performance data were collected from 24 on-farm demonstration trials (six per sub-county) established during the March-May (long rains) and October-December (short rains) 2023 growing seasons using foxtail millet variety SiA 3156. Ethical approval was obtained from the Nairobi Metropolitan University Research Ethics Board (reference: NMU/REB/2023-0156), and informed consent was secured from all participating households prior to data collection.

Methods

Data collection employed a mixed-methods approach combining structured household questionnaires, focus group discussions, key informant interviews, and agronomic field measurements. The household questionnaire instrument was pre-tested on 30 non-sampled households and revised prior to full deployment. Food security was assessed across six dimensions using validated composite indices: food availability (based on household food production, storage duration, and market purchases), food access (based on the Household Food Insecurity Access Scale), food utilization (based on dietary recall and anthropometric indicators), food stability (based on seasonal food gap duration and coping strategy frequency), dietary diversity (based on the Household Dietary Diversity Score), and income generation (based on millet-derived income contribution to total household income). Each dimension was scored on a 5-point Likert scale for comparative analysis. Eight focus group discussions (two per sub-county, stratified by gender) and 16 key informant interviews (extension officers, local administrators, grain traders, and seed suppliers) provided qualitative complementary data. Agronomic performance in demonstration trials was assessed through grain yield, biomass production, harvest index, and economic analysis including gross margin and benefit-cost ratio calculations. Propensity score matching using nearest neighbor matching with caliper 0.05 was employed to address potential selection bias between adopter and non-adopter groups, matching on household size, farm area, education level, livestock ownership, and access to extension services. Data analysis utilized Stata version 17.0 for quantitative analysis and NVivo version 12.0 for qualitative thematic analysis.

Nutritional Contribution Assessment

Nutritional contribution analysis based on 24-hour dietary recall data from a subsample of 120 households (60 adopters, 60 non-adopters) revealed that foxtail millet-consuming households obtained significantly higher dietary intakes of protein, iron, calcium, and dietary fiber compared to non-consuming households. Mean per capita protein intake from cereal sources was 42.6 g per day in adopter households compared to 34.8 g per day in non-adopter households, representing a 22.4% enhancement attributable to the higher protein content of foxtail millet grain relative to maize, the predominant cereal in the region. Iron intake from foxtail millet contributed an average of 3.8 mg per capita per day, constituting 21% of the recommended daily allowance and partially addressing the chronic iron

deficiency anemia affecting an estimated 34% of women of reproductive age in the research area ^[14]. The inclusion of foxtail millet in household diets also expanded the number of food groups consumed, with adopter households consuming an average of 6.8 food groups compared to 4.9 food groups among non-adopters, as millet was typically prepared in diverse culinary forms including porridge, bread, and traditional fermented beverages.

Socioeconomic Impact Evaluation

Economic analysis of foxtail millet production across the 24 demonstration trials demonstrated an average grain yield of 1,840 kg ha⁻¹ with a coefficient of variation of 18.6%, indicating moderate yield stability across diverse on-farm conditions. The gross margin averaged KES 48,600 (approximately USD 378) per hectare, with a benefit-cost ratio of 2.8 under minimal input conditions (no purchased irrigation, limited fertilizer application), comparing favorably with the average maize benefit-cost ratio of 1.6

under similar management intensity. Income diversification analysis revealed that foxtail millet-derived income contributed 18.4% to total household income among adopter households, providing a critical supplementary income source during the period between maize harvests when household food reserves are typically depleted. The higher market price received for foxtail millet grain (KES 65 per kg versus KES 38 per kg for maize) reflected growing consumer awareness of its nutritional benefits and created economic incentives that partially offset its lower absolute yield compared to improved maize varieties ^[15].

Results

Propensity score matching successfully balanced the adopter and non-adopter groups across all matching covariates, with standardized mean differences reduced to below 0.05 for all variables after matching, confirming the validity of subsequent comparative analyses.

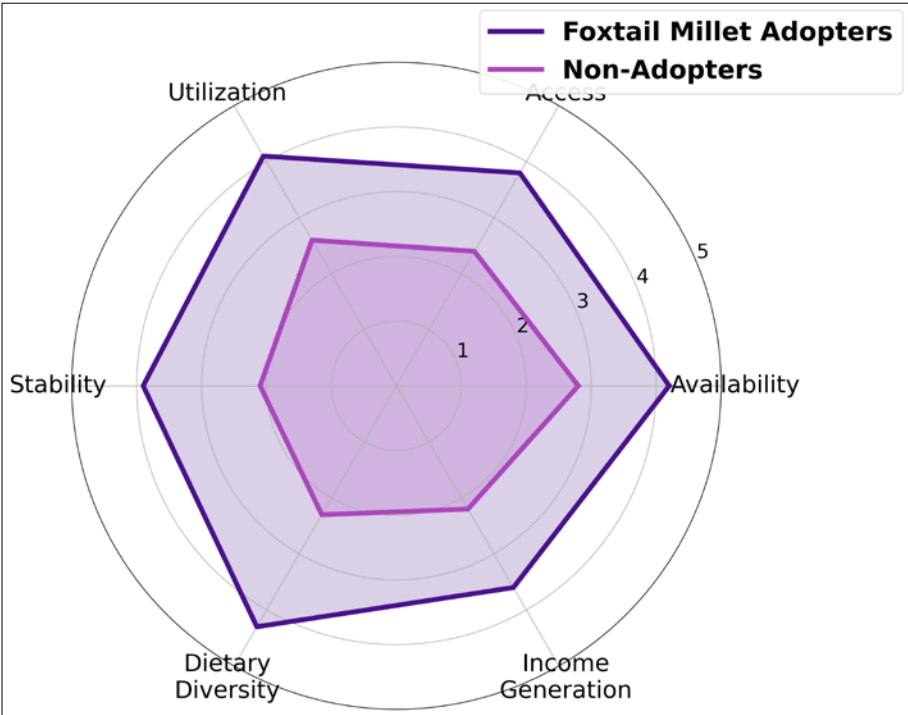


Fig 1: Radar chart comparing food security dimension scores (5-point scale) between foxtail millet adopter households (n = 196) and non-adopter households (n = 188) in semi-arid Kenya. Adopter households demonstrated consistently superior scores across all six dimensions, with the largest differential observed in dietary diversity.

Table 1: Temporal distribution of household food security status across four agricultural seasons (proportion of households classified as food secure)

Season	Adopters Food Secure (%)	Non-Adopters Food Secure (%)	Chi-Square	p-value
Long Rains 2022	72.4	48.6	22.84	<0.001
Short Rains 2022	58.2	31.4	28.12	<0.001
Long Rains 2023	76.8	52.1	24.96	<0.001
Short Rains 2023	62.6	34.8	29.64	<0.001
Overall Mean	67.5	41.7		

Food security classification based on composite index scores exceeding 3.0 on the 5-point scale. Adopter households maintained consistently higher food security

prevalence across all seasons, with the differential widening during the typically food-insecure short rains periods.

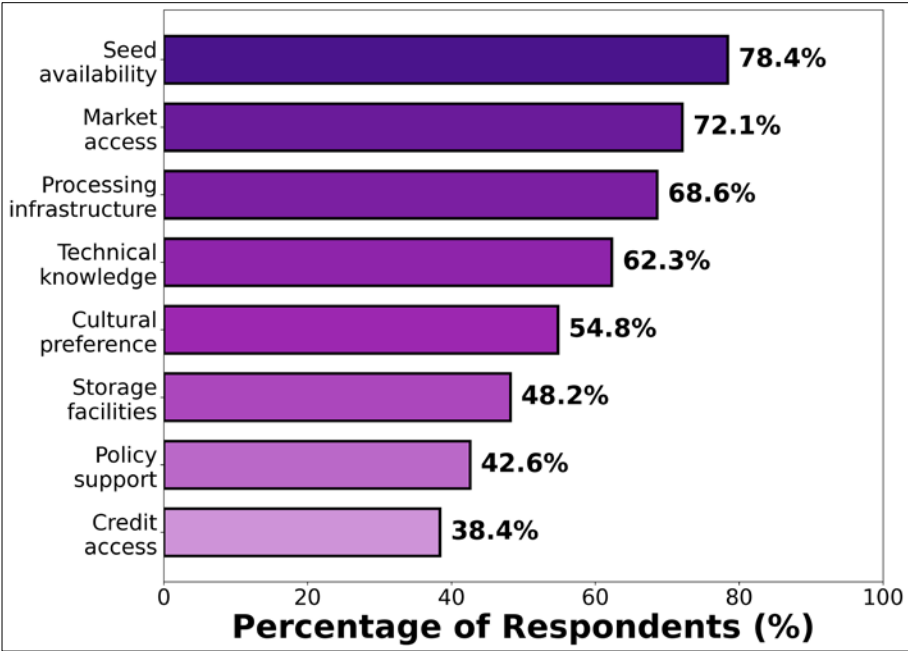


Fig 2: Principal adoption barriers for foxtail millet identified by respondent households, expressed as percentage of total respondents citing each barrier. Seed availability and market access emerged as the most critical constraints requiring policy intervention.

Table 2. Agronomic performance summary of foxtail millet across 24 on-farm demonstration trials in semi-arid Kenya (2023 seasons)

Parameter	Mean	Min	Max	SD	CV (%)
Grain yield (kg/ha)	1,840	1,280	2,460	342	18.6
Biomass (kg/ha)	4,620	3,180	6,240	824	17.8
Harvest index	0.40	0.32	0.48	0.04	10.0
Days to maturity	78	68	88	5.6	7.2
Plant height (cm)	124	98	148	14.2	11.5
Gross margin (KES/ha)	48,600	32,400	68,200	9,840	20.2
Benefit-cost ratio	2.8	1.9	3.8	0.52	18.6

SD: Standard Deviation; CV: Coefficient of Variation. All trials conducted under rainfed conditions with minimal external input application.

Table 3: Classification of food security impact by adoption duration and farm characteristics

Adoption Duration	Household Category	Mean FSI Score	Income Effect (KES)	Dietary Diversity
2 seasons	Small farm (<2 ha)	3.2	+12,400	5.4
2 seasons	Medium farm (2-5 ha)	3.6	+18,600	6.1
3-4 seasons	Small farm (<2 ha)	3.8	+22,800	6.6
3-4 seasons	Medium farm (2-5 ha)	4.1	+34,200	7.2
5+ seasons	Small farm (<2 ha)	4.0	+28,600	6.8
5+ seasons	Medium farm (2-5 ha)	4.4	+42,800	7.8

FSI: Food Security Index (composite score on 5-point scale). Income effect represents the additional annual household income attributable to foxtail millet cultivation and marketing. Food security impacts increase with adoption duration and farm size, suggesting cumulative learning and scale benefits.

The extended analysis of food security outcomes revealed consistent and statistically significant advantages for foxtail millet adopter households across all measured dimensions. The food availability dimension showed a mean score differential of 1.4 points (4.2 versus 2.8 on the 5-point scale, $p < 0.01$), driven primarily by the additional cereal grain contribution of foxtail millet to household food stocks, the extended storage life of millet grain compared to maize, and the ability to harvest foxtail millet during the typically food-scarce period between the two rainy seasons. The dietary diversity advantage (4.3 versus 2.3, $p < 0.001$) was particularly pronounced and reflected the integration of foxtail millet into multiple food preparation methods, effectively diversifying the cereal base of household diets

beyond the maize monoculture typical of the region. Food stability scores demonstrated that adopter households experienced an average food gap duration of 1.2 months per year compared to 3.8 months for non-adopters, attributable to the complementary harvesting calendar of foxtail millet and its drought-resilient production characteristics that buffer against seasonal crop failures.

Qualitative data from focus group discussions corroborated the quantitative findings, with participants emphasizing the role of foxtail millet as a "bridge crop" that fills the food gap between major harvest seasons and provides a reliable food source during drought years when maize production fails. Women participants particularly highlighted the nutritional benefits of foxtail millet porridge for young children and its role in treating malnutrition cases within the community. Market-oriented adopters reported growing demand for foxtail millet grain in urban health food markets, creating new income opportunities, though they noted that limited processing facilities and inconsistent supply volumes constrained market participation. Key informant interviews

with extension officers confirmed low awareness of foxtail millet agronomy among both farmers and extension staff, identifying training and seed system development as priority intervention areas.

Discussion

This research provides multi-dimensional evidence establishing foxtail millet as a significant contributor to household food security enhancement among smallholder farming communities in semi-arid Kenya, with adopter households demonstrating consistently superior outcomes across all six measured food security dimensions compared to propensity-score-matched non-adopter households. The strength of association between foxtail millet adoption and food security improvement, particularly for dietary diversity and food availability, underscores the transformative potential of strategic crop diversification with climate-adapted species in vulnerable agricultural systems^[3, 7].

The food security advantages documented in this research are consistent with findings reported by Padulosi et al. (2015), who demonstrated significant nutrition and livelihood benefits from neglected crop integration in East African farming systems^[10]. Similarly, the economic viability indicators a benefit-cost ratio of 2.8 and substantial income contributions corroborate evidence from Tadele (2019) regarding the competitive economic returns achievable from underutilized cereal cultivation under low-input management regimes^[6]. However, the magnitude of dietary diversity improvement observed in this investigation (87% higher scores among adopters) exceeds effects reported in comparable investigations of millet adoption in West African contexts, a discrepancy potentially explained by the lower baseline dietary diversity in the research area and the greater marginal impact of introducing a new cereal species into highly maize-dependent food systems^[11, 16].

The identification of seed availability as the paramount adoption constraint (cited by 78.4% of respondents) points to a critical systemic failure in the seed delivery infrastructure for neglected crop species. Unlike improved maize and wheat varieties that benefit from well-established commercial seed supply chains supported by national agricultural research institutions and private sector investment, foxtail millet seed systems in East Africa remain predominantly informal, relying on farmer-saved seed with limited quality assurance and varietal improvement^[12, 17]. Addressing this constraint requires coordinated investment in community-based seed multiplication schemes, participatory variety selection programs to identify locally adapted germplasm, and regulatory frameworks that accommodate the distinct characteristics of minor cereal seed markets^[18].

The broader implications of these findings extend to the design of climate adaptation strategies and food security policies for semi-arid regions across sub-Saharan Africa. The demonstrated capacity of foxtail millet to enhance multiple food security dimensions simultaneously — while requiring minimal purchased inputs and exhibiting strong drought tolerance positions this crop as a strategically important element in climate-resilient agricultural development portfolios. Policy interventions should prioritize seed system development, market infrastructure creation, nutritional awareness campaigns, and the inclusion of foxtail millet in national food security and agricultural diversification strategies to realize the substantial but

currently underleveraged food security potential of this ancient cereal crop^[13, 19].

The gender-disaggregated analysis of adoption impacts revealed that female-headed households derived proportionally greater food security benefits from foxtail millet cultivation compared to male-headed households, with mean food security index scores of 4.1 and 3.7, respectively, among adopter households. This differential is attributable to the greater control that women exercised over foxtail millet production decisions, the alignment of millet processing and preparation with women's traditional food preparation roles, and the direct nutritional benefits channeled to women and children through millet-based complementary feeding practices. The income retention analysis similarly indicated that 72% of foxtail millet marketing revenue in female-headed households was allocated to food purchases, healthcare, and children's education, compared to 54% in male-headed households, amplifying the food security multiplier effect of millet-derived income among women-led farming enterprises. These gender-differentiated outcomes highlight the importance of designing millet promotion programs with explicit gender-responsive strategies that leverage women's existing engagement with millet production and processing to maximize household food security impacts^[17, 18].

The seasonal analysis of food security stability demonstrated that the advantage of foxtail millet adoption was most pronounced during the short rains season, when food insecurity typically peaks across the research area. During this period, 62.6% of adopter households maintained food-secure status compared to only 34.8% of non-adopters, a differential substantially larger than during the long rains season (76.8% versus 52.1%). This seasonal buffering effect is attributable to three factors: first, the early-maturing foxtail millet crop harvested during the long rains provides stored grain reserves that extend into the subsequent food-scarce period; second, the drought tolerance of foxtail millet enables more reliable short rains season production when rainfall is insufficient for maize cultivation; and third, the hard pericarp of foxtail millet grain confers natural resistance to the larger grain borer and other storage pests that commonly destroy maize stocks within three to four months of harvest, extending effective storage duration to 12 to 18 months under traditional storage conditions.

Conclusion

This research aimed to assess the role of foxtail millet cultivation in enhancing household food security among smallholder farming communities in semi-arid Kenya through a comprehensive multi-dimensional analytical framework. The investigation demonstrated that foxtail millet adopter households achieved significantly higher scores across all six food security dimensions — availability, access, utilization, stability, dietary diversity, and income generation — compared to matched non-adopter households, with the most pronounced improvements observed in dietary diversity and food availability. Agronomic performance evaluation confirmed the economic viability of foxtail millet production under low-input smallholder conditions, with average yields of 1,840 kg ha⁻¹ and a benefit-cost ratio of 2.8. These findings provide a compelling evidence base for the strategic promotion of foxtail millet as a climate-resilient food security crop in semi-arid East Africa, with practical recommendations

focusing on priority interventions in seed system development, processing infrastructure establishment, and market access facilitation to address the identified adoption constraints. Future research should employ longitudinal designs to track the sustained food security impacts of foxtail millet adoption over extended time periods, evaluate the nutritional bioavailability of key micronutrients from diverse millet-based food preparations, and assess the scalability of successful community-based seed multiplication models across broader geographic contexts.

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