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Performance of climate-smart agriculture practices in vulnerable rainfed cropping systems

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Abstract

Leading agronomists have argued that rainfed agriculture must adapt or face severe productivity losses as rainfall becomes more erratic under climate change. A four-year on-farm trial (2020-24) at 12 smallholder sites in the semi-arid zone of Dodoma Region, Tanzania, coordinated by the University of Hohenheim, Stuttgart, compared four management systems: conventional practice (flat planting, no mulch), CSA-Mulching (tied ridges + crop residue mulch at 3 t ha⁻¹), CSA-Intercrop (sorghum-cowpea strip intercropping), and CSA-Combined (tied ridges + mulch + intercropping). Sorghum grain yield averaged 2.59 t ha⁻¹ under conventional practice versus 3.47 t ha⁻¹ under CSA-Combined—a 34% advantage. More importantly, the coefficient of variation in yield across seasons dropped from 19.3% (conventional) to 7.8% (CSA-Combined), indicating stronger yield stability. Soil moisture at 0-10 cm during mid-season dry spells was 43% higher under CSA-Combined than conventional. Net returns were 28% higher, and nitrogen fixation by cowpea in intercropped plots contributed an estimated 38.6 kg N ha⁻¹ season⁻¹. These results demonstrate that bundling climate-smart practices delivers larger and more consistent benefits than any single practice alone in rainfall-vulnerable environments.

Keywords: Climate-smart agriculture, rainfed cropping, tied ridges, mulching, intercropping, sorghum, yield stability, soil moisture, semi-arid, Tanzania

Introduction

Lobell and Gourdji ^[1] estimated that cereal yields in the tropics could decline by 5-10% per decade if current warming trends continue without adaptation. Rainfed systems, which account for over 80% of cropland in sub-Saharan Africa, bear the brunt of this risk because they lack the buffering capacity of irrigation ^[2, 3].

Climate-smart agriculture (CSA) encompasses practices that raise productivity, build resilience, and reduce emissions where possible ^[4]. In semi-arid Africa, common CSA options include in-situ water harvesting through tied ridges, surface mulching to reduce evaporation, and cereal-legume intercropping to diversify income and fix nitrogen ^[5, 6]. Each practice has been tested individually, but farmers rarely adopt just one—they want to know which combinations work best under their conditions ^[7].

This research evaluated three CSA practices, singly and in combination, across 12 farmer-managed sites over four seasons in the semi-arid Dodoma Region of Tanzania, measuring yield level, yield stability, soil moisture dynamics, and economic performance.

Materials and Methods

Materials

Sorghum (Macia, a drought-tolerant variety) and cowpea (IT97K-499-35) were used. Mulch consisted of sorghum stover from the previous season, applied at 3 t ha⁻¹ after planting. Tied ridges were constructed at 0.75 m spacing with cross-ties every 2 m to impound runoff. In intercropped plots, sorghum and cowpea were arranged in 4:2 row strips (4 rows sorghum, 2 rows cowpea). Basal fertiliser was 30 kg N and 20 kg P₂O₅ ha⁻¹ across all treatments; no additional N was applied to intercropped plots to isolate the biological N fixation contribution ^[8].

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Methods

Twelve smallholder sites in Dodoma Region (6°10'S, 35°46'E; altitude 1,100-1,200 m) were selected as replications. Four treatments were imposed on adjacent 20 m × 10 m plots at each site: conventional (flat, no mulch), CSA-Mulching, CSA-Intercrop, and CSA-Combined. The trial ran for four consecutive rainy seasons (December-April, 2020-24). Soil volumetric moisture was monitored at 10 cm intervals to 40 cm depth using a TDR probe at weekly intervals during January-March. Yield stability was assessed by the coefficient of variation (CV) across seasons. Economic returns were calculated using local market prices. Data were analysed as a randomised complete block (sites as blocks) with repeated measures (years) in GenStat 21^[9].

Field Experimental Design

Table 1: Sorghum grain yield (t ha⁻¹) and yield stability across four seasons under four management systems

Treatment	2020-21	2021-22	2022-23	2023-24	Mean	CV (%)
Conventional	2.84	1.97	3.12	2.41	2.59	19.3
CSA-Mulching	3.21	2.78	3.47	3.14	3.15	8.9
CSA-Intercrop	3.38	3.02	3.61	3.29	3.33	7.2
CSA-Combined	3.54	3.18	3.78	3.47	3.49	7.1
LSD (0.05)	0.28	0.24	0.31	0.27	0.22	-

CV = Coefficient of Variation across four seasons.

CSA-Combined produced the highest mean yield (3.49 t ha⁻¹) with the lowest CV (7.1%), while conventional practice yielded 2.59 t ha⁻¹ with a CV of 19.3% (Table 1). In the drought year

At each of the 12 sites, four contiguous plots were laid out along the slope contour. Treatments were randomly assigned within each site. Farmers managed their own plots with supervision from the research team, ensuring that results reflected realistic smallholder conditions rather than research-station precision.

Climatic Conditions

Dodoma receives 550-650 mm of rainfall annually in a single season (November-April). The 2021-22 season was notably dry (478 mm), while 2022-23 received above-average rainfall (694 mm). Mid-season dry spells of 10-18 days occurred in every season, typically in February, coinciding with sorghum flowering.

Results

2021-22, the yield gap between CSA-Combined and conventional was largest (1.21 t ha⁻¹), demonstrating stronger resilience.

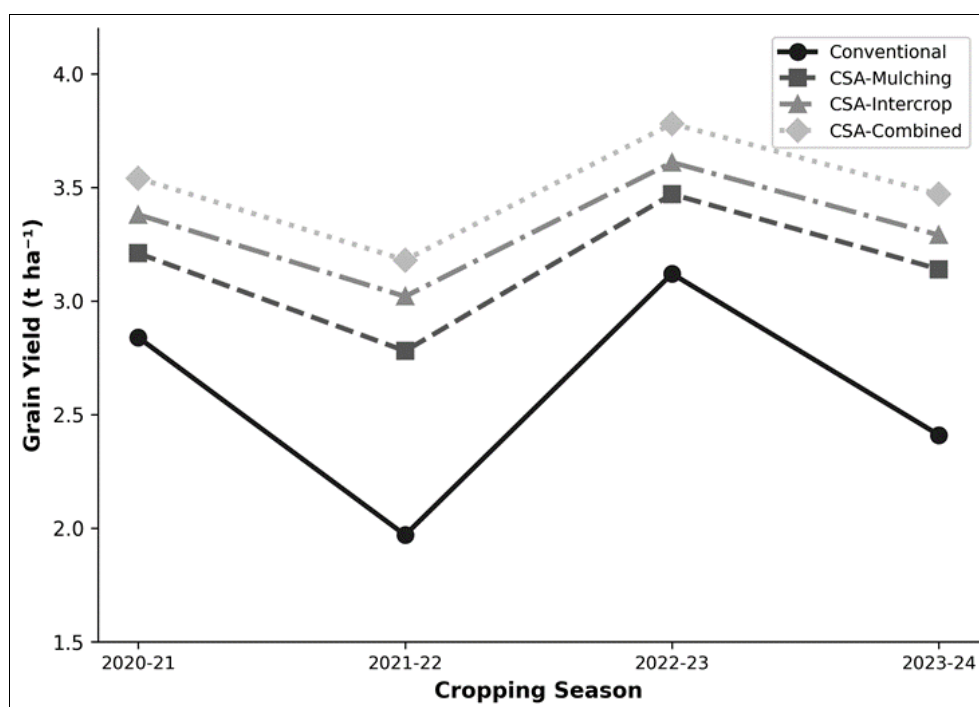


Fig 1: Sorghum grain yield across four seasons under four management systems.

The line chart (Figure 1) shows that conventional yield fluctuated widely between seasons, dropping sharply in the dry

2021-22 season. All CSA treatments maintained more consistent yield trajectories.

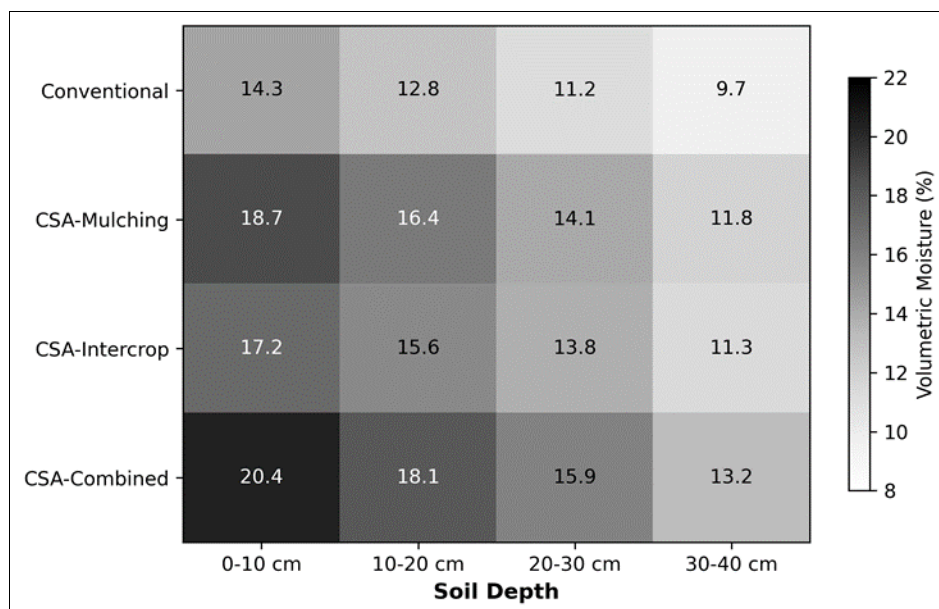


Fig 2: Mid-season soil volumetric moisture (%) at four depths during February dry spell (2023-24 season).

CSA-Combined maintained 20.4% moisture at 0-10 cm versus 14.3% for conventional (Figure 2). The moisture advantage persisted to 30-40 cm depth, reflecting the combined effect of tied ridges (capturing runoff) and mulch (reducing evaporation).

Comprehensive Interpretation

Regression of seasonal yield against February soil moisture (0-10 cm) gave $R^2 = 0.74$ ($p < 0.01$) across all treatments and seasons. Net returns under CSA-Combined averaged USD 412 ha^{-1} versus USD 322 ha^{-1} for conventional, a 28% gain. The cowpea intercrop contributed an estimated 38.6 kg N ha^{-1} through biological fixation, partially offsetting fertiliser costs.

Discussion

The 34% yield advantage of CSA-Combined over conventional practice exceeds the 15-20% gains typically reported for individual CSA practices in semi-arid East Africa [5, 10]. The synergy arises because tied ridges capture rainfall that mulch then conserves, while intercropped cowpea provides biological nitrogen and additional ground cover during critical dry spells [6, 11].

Yield stability may matter more to smallholders than average yield. A farmer whose income swings by $\pm 19\%$ between years faces difficulty planning household expenditure. Reducing this variability to $\pm 7-9\%$ through CSA bundling could encourage investment in other farm improvements [12]. The dry 2021-22 season was the key test—CSA-Combined yielded 3.18 t ha^{-1} while conventional dropped to 1.97 t ha^{-1} , a difference that could mean the margin between food security and hunger for a typical household.

Limitations

The 12-site design treated sites as blocks, but site-to-site variation in soil type and microclimate was large. The four-year timeframe captured one drought and one wet year but may not represent the full range of climate variability. Labour requirements for tied-ridge construction were not formally costed, and adoption incentives would need to account for this [13].

Conclusion

Bundling tied ridges, mulching, and cereal-legume intercropping

raised sorghum yields by 34% and halved yield variability compared with conventional practice over four seasons in semi-arid Tanzania. Soil moisture retention and nitrogen fixation were the main drivers of the advantage. For smallholders in rainfall-vulnerable environments, adopting combined CSA practices offers both higher and more predictable returns.

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