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Calibration and Validation of Inductive cum Targeted Yield Fertiliser Equations for Finger Millet on a Red *Alfisol* of Tamil Nadu

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Abstract

Soil-test-based fertiliser prescriptions are unavailable for finger millet (*Eleusine coracana*) on the red *Alfisols* of peninsular India. Targeted-yield equations were calibrated for cv. ATL 1 on a *Typic Rhodustalf* (Palaviduthi series) in Tamil Nadu by the inductive approach: graded NPK on fodder sorghum created a fertility gradient, a 72-plot test-crop experiment combined 24 NPK treatments, three strips and farmyard manure (FYM) at 0, 6.25 and 12.5 t ha^{-1} and two validation trials on separate farms followed in the next season. Finger millet required 21.1 kg N, 7.5 kg P_2O_5 and 26.0 kg K_2O per tonne of grain. Soil supplied 14.86, 19.19 and 18.95% of N, P_2O_5 and K_2O uptake, fertiliser 44.16, 32.79 and 59.75% and FYM 28.47, 11.77 and 33.78%; FYM at 12.5 t ha^{-1} replaced about 40 kg N, 25 kg P_2O_5 and 35 kg K_2O. All twelve target-by-farm combinations reached 91.3–103.9% of the target (bias −113 kg ha^{-1}, RMSE 170 kg ha^{-1}; mean 99.0% for STCR-IPNS, 95.0% for STCR-NPK). STCR-IPNS for 4.0 t ha^{-1} yielded 3849 kg ha^{-1}, 39.0, 17.1 and 57.0% above blanket, blanket plus FYM and farmers' practice, with a benefit–cost ratio of 1.94 and 18–46% less fertiliser than

STCR-NPK at equal targets. Counting FYM nutrients removed the response-ratio advantage of IPNS. The 50% and 150% dose limits governed the highest NPK-alone and lowest IPNS targets. One principal component explained 96.7% of the variance in 15 traits and ranked treatments identically on both farms. Soil K at both validation farms exceeded the calibrated range.

Keywords: *Eleusine coracana*; soil test crop response; targeted yield; integrated plant nutrition system; fertiliser prescription equation; *Typic Rhodustalf*; principal component analysis

1. Introduction

Finger millet (*Eleusine coracana* (L.) Gaertn.) is a drought-tolerant small millet whose grain contains 344 mg of calcium per 100 g (APEDA, n.d.). India produced 1.70 Mt of finger millet in 2021–22, of which Karnataka supplied 66% and Tamil Nadu 13% (APEDA, n.d.). Growers in the region commonly apply a fixed blanket dose, set at 60:30:30 kg $N:P_2O_5:K_2O$ ha^{-1} in this study, although soils differ widely in the N, P and K they supply and the national NPK use ratio is unbalanced (Katyal and Chaudhari, 2021). A fixed dose over-fertilises fertile fields, under-supplies poor ones and ignores the nutrients in farmyard manure (FYM). Long-term experiments on rainfed *Alfisols* show that FYM combined with fertiliser sustains finger millet yield and soil quality (Sathish *et al*., 2016; Sharma *et al*., 2016; Prabhakar *et al*., 2023). They do not state how much fertiliser a particular field needs.

The targeted-yield approach of Truog (1960) and Ramamoorthy *et al*. (1967) converts a yield target and a soil test value into a fertiliser dose with three crop-specific parameters: the nutrient required per unit of grain and the percentages of nutrient uptake supplied by soil and by fertiliser. A fourth parameter, the contribution from FYM, extends the equations to the integrated plant nutrition system (IPNS). Because soil, season and management confound calibration on farmers' fields, the inductive approach builds the required range of fertility inside one field with an exhaustive gradient crop and grows the test crop on that gradient (Ramamoorthy *et al*., 1967; Naveen *et al*., 2016). Equations of this kind exist for pearl millet, barnyard millet, castor and beetroot in Tamil Nadu (Santhi *et al*., 2011; Udayakumar and Santhi, 2017; Selvam *et al*., 2022; Abishek *et al*., 2022; Narmada *et al*., 2023), for finger millet on an *Alfisol* of Karnataka (Basavaraja *et al*., 2017) and on *Mollisols* of northern India (Ayushi *et al*.,

2022) and for barnyard millet in southern India (Rangaiah *et al*., 2026). Independent validation of finger millet equations was reported from the southern dry zone of Karnataka, where a target of 40 q ha^{-1} produced 42.65 and 42.00 q ha^{-1} at two locations (Murthy *et al*., 2023). Targeted-yield prescriptions have also been used as the basis of soil-quality studies and on the same Palaviduthi series in Dindigul district an FYM-adjusted prescription reached 105.8% of a greengram target and raised enzyme activity and a PCA-derived soil quality index (Abhirami *et al*., 2026).

Equations validated on independent farms are not available for finger millet on the red *Alfisols* of Tamil Nadu. The gradient crop and the basic parameters of the present calibration were summarised in two short reports (Asan Mohamed *et al*., 2023; Mohamed *et al*., 2023); the accuracy of the prescriptions, their efficiency and the multi-trait response of the crop were not. Three points remain unresolved. Validation reports usually express accuracy as per cent achievement alone (Kanchana *et al*., 2020; Murthy *et al*., 2023) and bias and error are seldom stated. The maintenance and maximum dose limits of the AICRP-STCR protocol alter the dose at both ends of the range and their effect on accuracy is not separated from that of the equations. The value of the manure credit in terms of fertiliser saved, efficiency and profit depends on how the nutrients in FYM are counted.

The objectives were to (i) calibrate and present prescription equations for NPK alone and for IPNS on a *Typic Rhodustalf*; (ii) quantify FYM substitution and critical soil test values; (iii) test the prescriptions on two independent farms in the following season and report bias and RMSE in addition to per cent achievement; (iv) separate the response per unit of purchased fertiliser from the response per unit of all nutrients applied; (v) summarise the multi-trait response by principal component analysis in R; and (vi) map the sites and compare their soil test values with the calibrated domain using geospatial tools.

2. Materials and methods

2.1 Study area and soils

The work was done on farmers' fields in Dindigul district, Southern Agro-climatic Zone of Tamil Nadu (Fig. 1). Phases I and II were conducted at Thoppupatti village, Vedasandur block (10°34′49″ N, 78°04′35″ E; 261 m a.s.l.). The soil is a *Typic Rhodustalf* of the Palaviduthi series: red, non-calcareous, moderately deep sandy loam

with 18.4% clay and 17.2% silt, neutral (pH 7.49) and non-saline (EC 0.13 dS m^{-1}), with a CEC of 12.9 cmol(p^+) kg^{-1} and organic C of 6.5 g kg^{-1}. Available N, P and K (215, 21.3 and 219 kg ha^{-1}) rated low, medium and medium, DTPA-extractable Zn, Fe, Mn and Cu were sufficient and the P- and K-fixing capacities were 100 kg ha^{-1} each. The validation trials were laid out on two other farms of the same series in Guziliamparai block, at Ayyakannur and Palayam (Table 1). Irrigation water was moderately saline at Thoppupatti and Ayyakannur and non-saline at Palayam and residual sodium carbonate was negative at all sites.

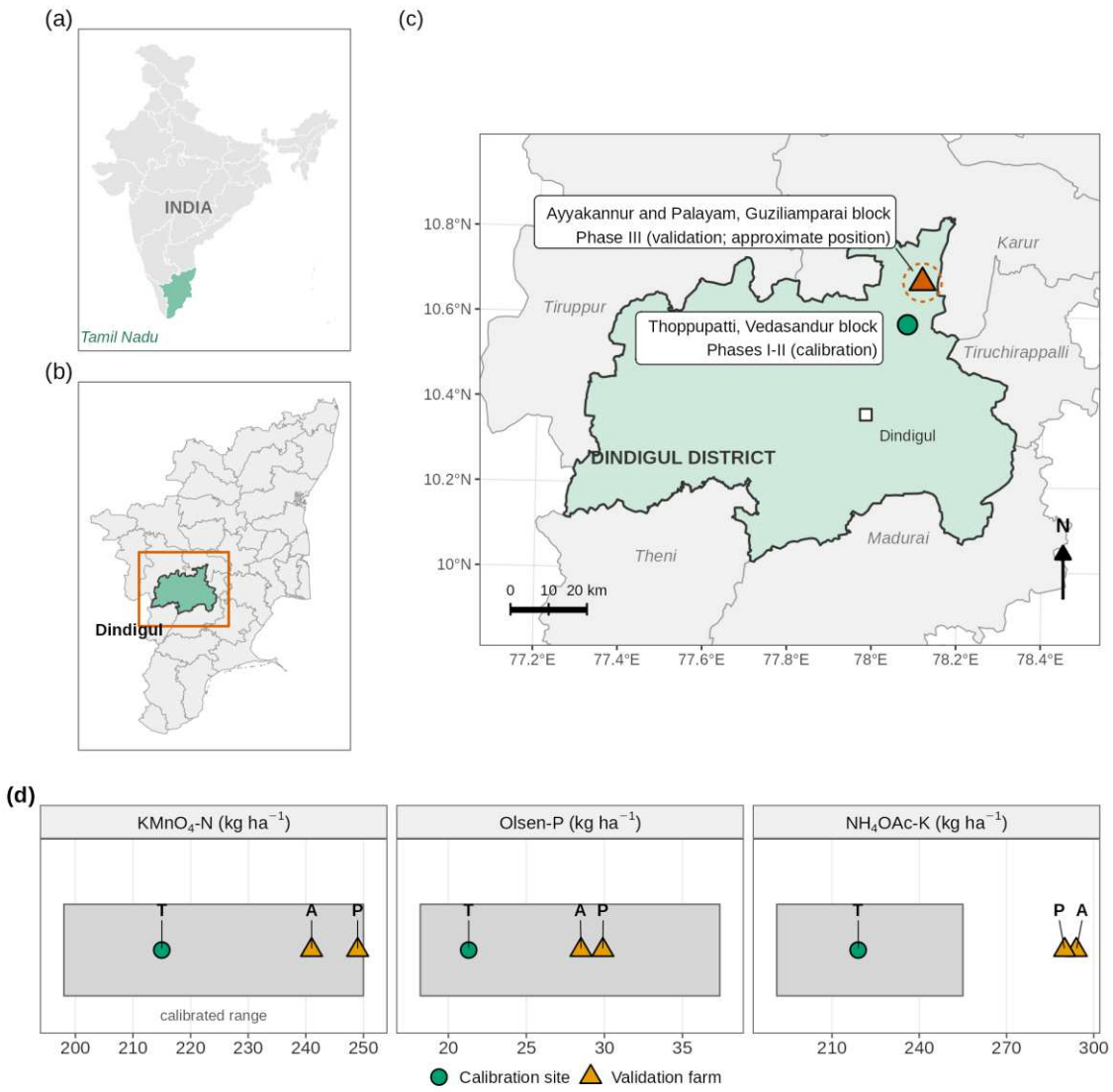


Fig. 1. Study area. (a) India with Tamil Nadu highlighted. (b) Tamil Nadu districts with Dindigul highlighted and the extent of panel c outlined. (c) Dindigul district with the calibration site (Thoppupatti, circle) and the validation farms (Ayyakannur and Palayam, triangle; the dashed circle marks the approximate, block-level position). (d) Soil test values of the three sites (T, Thoppupatti; A, Ayyakannur; P, Palayam) against the calibrated range (grey bar). District and state boundaries: Census of India 2011, compiled by the DataMeet India community (CC BY 4.0). Map drawn in R with the sf package.

Table 1. Location and initial soil properties of the three sites.

Property	Thoppupatti	Ayyakannur	Palayam
Phase	I–II (calibration)	III (validation)	III (validation)

Property	Thoppupatti	Ayyakannur	Palayam
Block	Vedasandur	Guziliamparai	Guziliamparai
Soil series	Palaviduthi	Palaviduthi	Palaviduthi
pH	7.49	7.04	7.28
EC (dS m^{-1})	0.13	0.11	0.09
$KMnO_4$-N (kg ha^{-1})	215	241	249
Olsen-P (kg ha^{-1})	21.3	28.5	29.9
NH_4OAc-K (kg ha^{-1})	219	294	290
Irrigation water EC (dS m^{-1})	3.02	2.48	0.81
Irrigation water SAR	5.06	5.05	1.91

EC, electrical conductivity; SAR, sodium adsorption ratio. Soil test methods are given in Section 2.3.

2.2 Phases I and II: fertility gradient and test crop

Fig. 2 summarises the design. In Phase I, fodder sorghum (cv. CO 30) was grown from 24 December 2021 to 28 February 2022 on three adjacent strips of 600 m² that received no NPK (N0P0K0), a first level (N1P1K1) or twice that level (N2P2K2). N1 was the blanket dose for fodder sorghum (90 kg N ha^{-1}) and P1 and K1 were set to the P- and K-fixing capacities of the soil (229 kg P_2O_5 and 121 kg K_2O ha^{-1}). The gradient was confirmed from soil test values, fodder yield, nutrient uptake and soil biology (Asan Mohamed *et al*., 2023).

In Phase II, finger millet (cv. ATL 1) was grown on the same strips from 4 April to 10 August 2022 at 30 × 10 cm in plots of 25 m². Following the AICRP-STCR protocol, each strip carried 24 treatments (21 fertiliser combinations and three absolute controls) at four levels of N (0, 30, 60 and 90 kg ha^{-1}), P_2O_5 (0, 15, 30 and 45 kg ha^{-1}) and K_2O (0, 15, 30 and 45 kg ha^{-1}) in a fractional factorial design randomised in both directions. FYM at 0, 6.25 or 12.5 t ha^{-1} was superimposed on three blocks of eight treatments in each strip, which gave 72 plots. Half of the N and all of the P_2O_5 and K_2O were applied basally and the remaining N at tillering. Composite soil samples (0–15 cm) were drawn from every plot before planting.

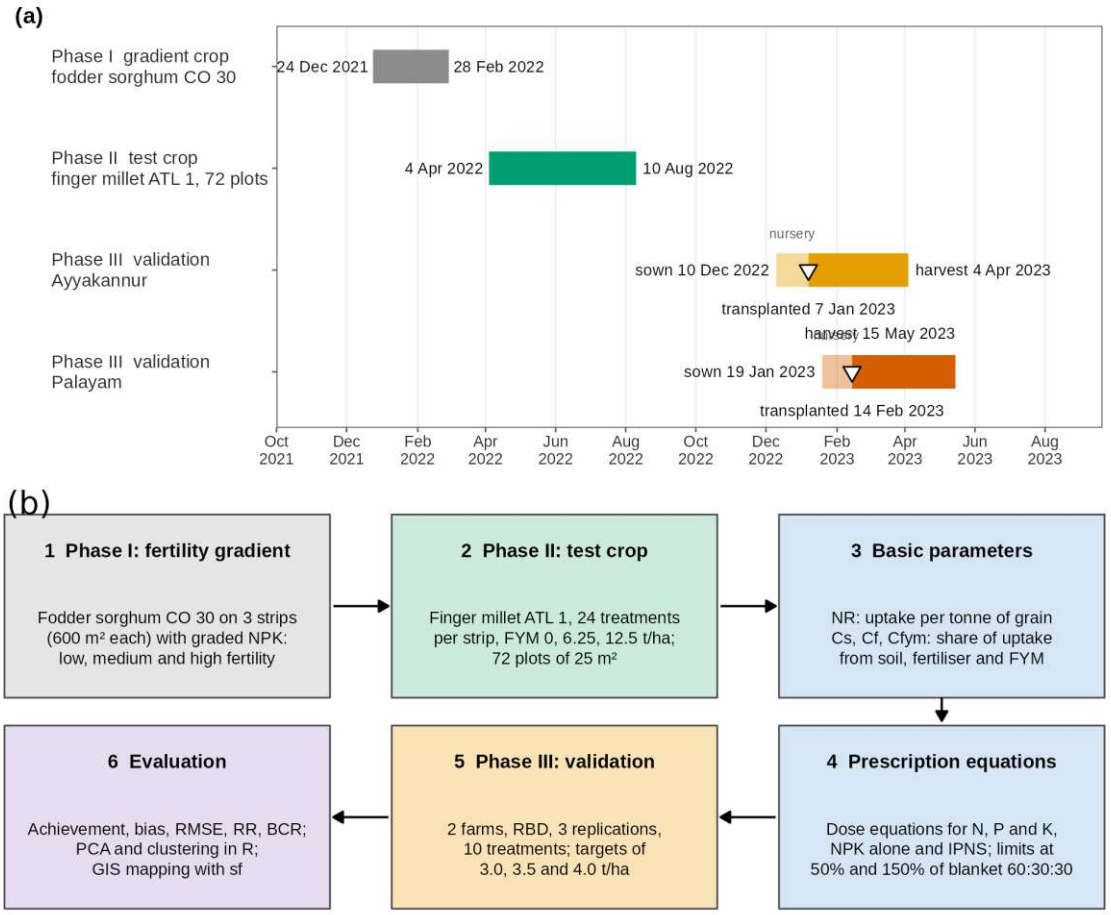


Fig. 2. Experimental timeline and workflow. (a) Crop calendar of the gradient crop (Phase I), the test crop (Phase II) and the two validation trials (Phase III). (b) Sequence from the fertility gradient to the prescription equations and their validation.

2.3 Soil and plant analysis

Soil was analysed for alkaline $KMnO_4$-N (Subbiah and Asija, 1956), Olsen-P (Olsen *et al.*, 1954) and NH_4OAc-K by flame photometry (Stanford and English, 1949). Grain and straw from each plot were dried at 60 °C, ground and digested (di-acid for N, tri-acid for P and K) and analysed for N by micro-Kjeldahl, for P by the vanadomolybdate method and for K by flame photometry (Humphries, 1956; Piper, 1966). Uptake is nutrient concentration multiplied by the dry matter of grain plus straw. P and K uptake are expressed as elemental P and K and the factors 2.29 and 1.21 convert them to P_2O_5 and K_2O. FYM was analysed for moisture, N, P and K.

2.4 Basic parameters and prescription equations

Nutrient requirement (NR, kg t^{-1}) is the total uptake of a nutrient divided by grain yield. The contribution from soil, Cs, is the uptake in the absolute control divided by its soil test value and multiplied by 100 (Eq. 1). The contribution from fertiliser, Cf, is the uptake in a fertilised plot minus the soil contribution, divided by the fertiliser dose and multiplied by 100 (Eq. 2). The contribution from FYM, Cfym, follows from FYM-treated plots after both the soil and the fertiliser contributions are deducted (Eq. 3).

$$Cs = (U_0 / S_0) \times 100 \quad (1)$$

$$Cf = [(U_F - S_F \cdot Cs/100) / F] \times 100 \quad (2)$$

$$Cfym = [(U_O - S_O \cdot Cs/100 - F_O \cdot Cf/100) / O] \times 100 \quad (3)$$

Here U is nutrient uptake (kg ha^{-1}), S the soil test value, F the fertiliser dose and O the nutrient applied through FYM, with the subscripts 0, F and O denoting control, fertilised and FYM-treated plots. The prescription equations are

$$F_N = (NR_N / (Cf_N/100)) \cdot T - (Cs_N/Cf_N) \cdot SN - (Cfym_N/Cf_N) \cdot ON \quad (4)$$

$$F_{P2O5} = (NR_{P2O5} / (Cf_{P2O5}/100)) \cdot T - (Cs_{P2O5}/Cf_{P2O5}) \cdot 2.29 \cdot SP - (Cfym_{P2O5}/Cf_{P2O5}) \cdot 2.29 \cdot OP \quad (5)$$

$$F_{K2O} = (NR_{K2O} / (Cf_{K2O}/100)) \cdot T - (Cs_{K2O}/Cf_{K2O}) \cdot 1.21 \cdot SK - (Cfym_{K2O}/Cf_{K2O}) \cdot 1.21 \cdot OK \quad (6)$$

where T is the yield target (t ha^{-1}), SN, SP and SK are the soil test values and ON, OP and OK are the elemental N, P and K supplied by FYM (kg ha^{-1}). The factors 2.29 and 1.21 convert P to P_2O_5 and K to K_2O; they are part of the published coefficients, so OP and OK must be entered as elemental P and K. The equations for NPK alone omit the FYM term. As in AICRP-STCR, a calculated dose below 50% of the blanket dose (60:30:30 kg N:P_2O_5:K_2O ha^{-1}) is replaced by a maintenance dose equal to 50% of the blanket dose (30:15:15) and a dose above 150% of the blanket dose is capped at that value (90:45:45). The critical soil test value is the value at which the calculated dose is zero.

2.5 Phase III: validation trials and performance indices

Two trials were run in the following season on farmers' fields at Ayyakannur (sown 10 December 2022, transplanted 7 January 2023, harvested 4 April 2023) and Palayam (sown 19 January 2023, transplanted 14 February 2023, harvested 15 May

2023). Each trial was a randomised block design with ten treatments and three replications in plots of 25 m² at 30 × 10 cm. The treatments were T1, blanket dose (60:30:30); T2, blanket dose plus FYM at 12.5 t ha^{-1}; T3–T5, STCR-NPK alone for 3.0, 3.5 and 4.0 t ha^{-1}; T6–T8, STCR-IPNS (12.5 t FYM ha^{-1} plus fertiliser) for the same targets; T9, farmers' practice (40:20:20); and T10, absolute control. Doses were calculated from the initial soil test values of each farm (Table 6). The FYM applied in the validation trials contained 24% moisture and 0.66, 0.32 and 0.54% N, P and K on a dry-weight basis. At harvest we recorded plant height, leaf area index (LAI), productive tillers m^{-2}, root length, fingers per earhead, earhead length and weight, test weight, SPAD-502 reading, leaf N and moisture, grain yield and N, P and K uptake.

Per cent achievement is observed yield divided by the target and multiplied by 100 (Eq. 7); a prescription is regarded as valid when it falls within ±10% (Velayutham *et al*., 1985). Bias is the mean of ($Y - T$) and RMSE the square root of the mean of ($Y - T$)² over the twelve STCR prescriptions. The response ratio per kg of fertiliser, RR_F, is the yield gain over the absolute control of the same farm divided by the N + P_2O_5 + K_2O applied as fertiliser (Eq. 8). Because FYM also supplies nutrients, RR_T divides the same gain by the fertiliser plus the fertiliser equivalent of the FYM (*FE*, 88 kg ha^{-1} of N + P_2O_5 + K_2O for 12.5 t FYM of the validation composition; Eq. 9). The benefit–cost ratio (BCR) is gross return divided by total cost of cultivation, undiscounted (Gittinger, 1982), as recorded for each farm.

$$\text{Achievement (\%)} = (Y / T) \times 100 \tag{7}$$

$$RR_F = (Y - Y_0) / F \tag{8}$$

$$RR_T = (Y - Y_0) / (F + FE) \tag{9}$$

2.6 Statistical, multivariate and geospatial analysis

Validation data were analysed as a randomised block design by ANOVA and means were separated at the critical difference (P = 0.05; Gomez and Gomez, 1984) in IBM SPSS 22; the letters in Table 6 come from those analyses. Means of the two farms are pooled descriptively. All other calculations and all figures were produced in R 4.3.3 (R Core Team, 2024). Accuracy was summarised as per cent achievement, bias, RMSE and the regression of observed yield on target and approach and the ready reckoners were recomputed from unrounded parameters.

Fifteen traits (grain yield; N, P and K uptake; plant height; LAI; tillers m^{-2}; root length; fingers per earhead; earhead length and weight; test weight; SPAD reading; leaf N; leaf moisture) were standardised within each farm to remove farm effects and analysed by principal component analysis (PCA; FactoMineR 2.9, Lê *et al*., 2008; n = 20 treatment-by-farm means). The number of components was judged against Horn's (1965) parallel analysis (1000 random normal data sets, 95th percentile). Fertiliser applied, RR_F, RR_T and BCR entered the analysis as supplementary variables, which means that they were correlated with the component scores without influencing the components. Treatment profiles were clustered by average linkage on Euclidean distance and displayed with pheatmap 1.0.12 (Kolde, 2019). Graphics were drawn with ggplot2 3.4.4 (Wickham, 2016), patchwork 1.2.0 (Pedersen, 2024) and factoextra 1.0.7 (Kassambara and Mundt, 2020).

Spatial data were handled with the sf package (version 1.0-15; Pebesma, 2018). Census of India 2011 district and state boundaries compiled by the DataMeet India community (DataMeet, n.d.) were projected to the India NSF Lambert conformal conic system (EPSG:7755). Site coordinates were stored in WGS 84 in a GeoPackage that opens directly in QGIS or ArcGIS and the soil test values of the three sites were compared with the calibrated range of the strips.

3. Results

3.1 Calibration dataset

Pre-planting soil test values spanned 198–250 kg ha^{-1} of $KMnO_4$-N, 18.2–37.4 kg ha^{-1} of Olsen-P and 191–255 kg ha^{-1} of NH_4OAc-K across the three strips (Table 2, Fig. 3a), which defines the calibrated range of the equations. Grain yield and nutrient uptake rose from strip I to strip III (Fig. 3a,b). Plots that received NPK averaged 2579 kg ha^{-1} against 1712 kg ha^{-1} in the absolute controls, a gain of 50.6%. The response to each nutrient increased with dose and reached 1020 kg ha^{-1} at 90 kg N, 597 kg ha^{-1} at 45 kg P_2O_5 and 590 kg ha^{-1} at 45 kg K_2O; the response ratio also rose with level (9.5–11.3, 11.0–13.3 and 11.0–13.1 kg grain per kg of N, P_2O_5 and K_2O). The highest yield (3962 kg ha^{-1}) came from 90:30:30 kg N:P_2O_5:K_2O with 12.5 t FYM ha^{-1} in strip III and the lowest (1324 kg ha^{-1}) from the unfertilised control in strip I.

Table 2. Pre-planting soil test values (kg ha^{-1}), grain yield (kg ha^{-1}) and nutrient uptake (kg ha^{-1}) of finger millet in the three fertility strips of the test-crop experiment: mean (minimum–maximum) of 24 plots per strip.

Strip	$KMnO_4$-N	Olsen-P	NH_4OAc-K	Grain yield	N uptake	P uptake	K uptake
I	200 (198–207)	22.1 (18.2–24.5)	197 (191–200)	2100 (1324–2779)	42.2 (28.5–59.0)	6.1 (3.9–8.8)	48.9 (35.5–62.1)
II	224 (221–231)	29.7 (26.5–31.9)	226 (223–233)	2719 (1731–3614)	56.6 (35.1–85.0)	8.5 (5.3–13.5)	59.5 (45.0–76.4)
III	244 (240–250)	34.3 (32.0–37.4)	249 (245–255)	2917 (1895–3962)	70.7 (45.8–89.5)	13.7 (6.0–18.9)	64.0 (50.0–85.5)

Uptake of P and K is given as elemental P and K.

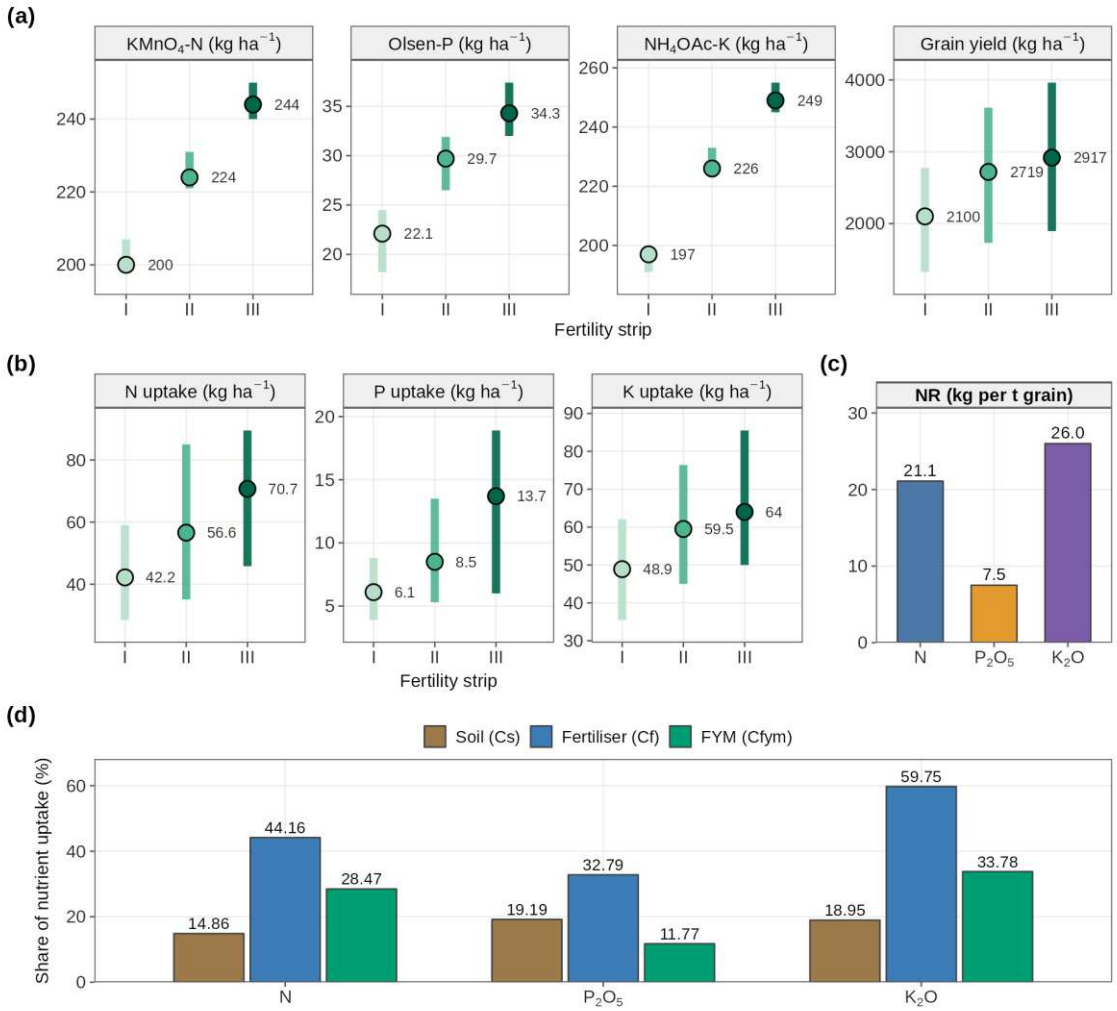


Fig. 3. Calibration dataset and basic parameters. (a) Pre-planting soil test values and grain yield and (b) N, P and K uptake in the three fertility strips (points, mean of 24 plots; bars, minimum to maximum). (c) Nutrient requirement (NR) per tonne of grain. (d) Share of nutrient uptake supplied by soil (Cs), fertiliser (Cf) and FYM (Cfym).

3.2 Basic parameters and prescription equations

Finger millet needed 21.1 kg N, 7.5 kg P_2O_5 and 26.0 kg K_2O per tonne of grain, in the order K_2O > N > P_2O_5 (Table 3, Fig. 3c). Soil supplied 14.86–19.19% of uptake, fertiliser 32.79–59.75% and FYM 11.77–33.78% (Fig. 3d). Per unit of nutrient applied, FYM was 64, 36 and 57% as effective as fertiliser N, P_2O_5 and K_2O (Cfym/Cf). The prescription equations for IPNS, with T in t ha^{-1}, are

$$F_N = 47.8\ T - 0.34\ SN - 0.64\ ON \quad (10)$$

$$F_{P2O5} = 22.9\ T - 1.34\ SP - 0.82\ OP \quad (11)$$

$$F_{K2O} = 43.6\ T - 0.38\ SK - 0.68\ OK \quad (12)$$

and the equations for NPK alone omit the last term. Each additional 20 kg of $KMnO_4$-N, 3 kg of Olsen-P or 20 kg of NH_4OAc-K lowers the dose by 6.7 kg N, 4.0 kg P_2O_5 and 7.7 kg K_2O.

Table 3. Basic parameters of the targeted-yield model for finger millet (cv. ATL 1) and coefficients of the prescription equations.

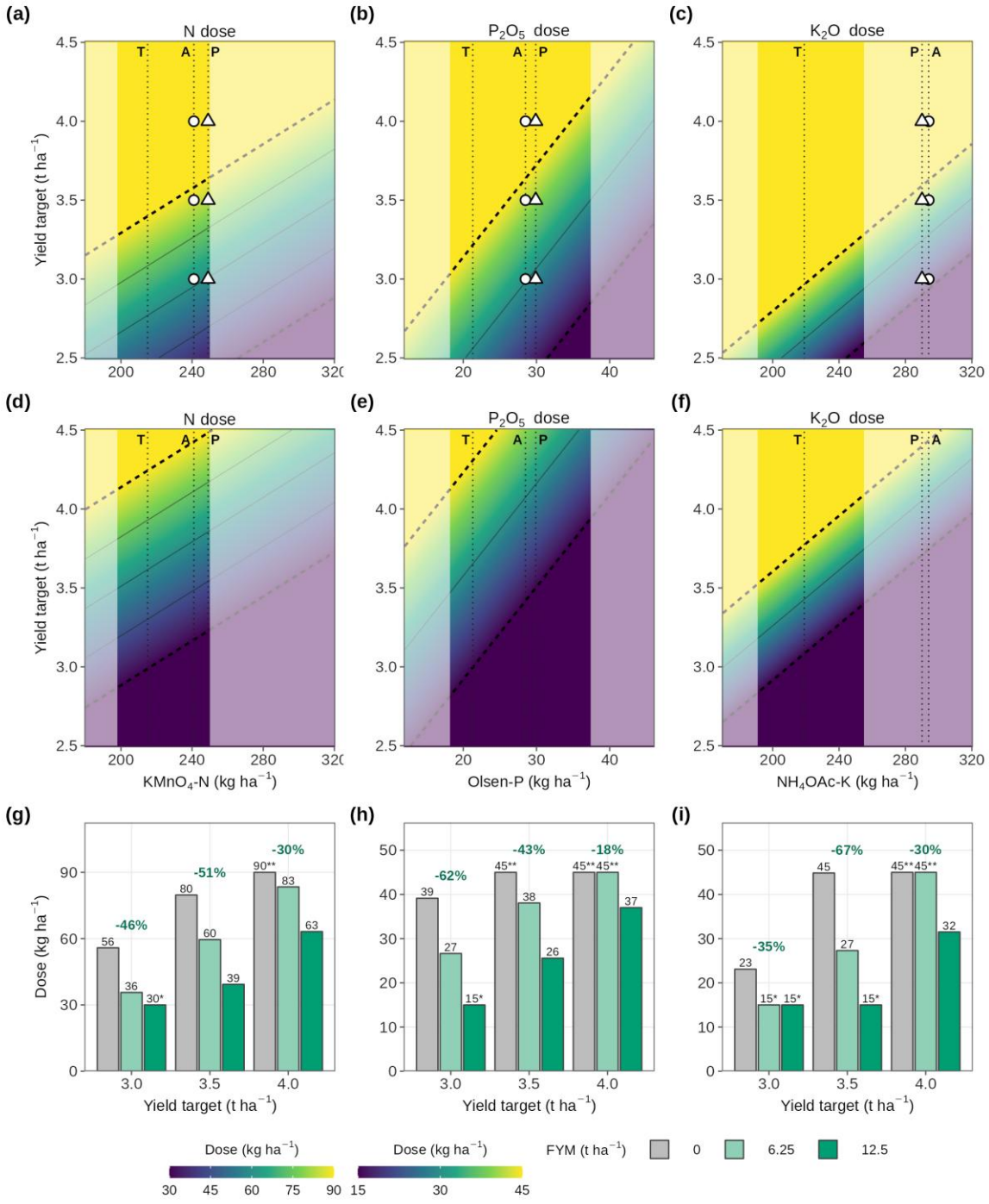
Parameter	N	P_2O_5	K_2O
Nutrient requirement, NR (kg per tonne of grain)	21.1	7.5	26.0
Contribution from soil, Cs (%)	14.86	19.19	18.95
Contribution from fertiliser, Cf (%)	44.16	32.79	59.75
Contribution from FYM, Cfym (%)	28.47	11.77	33.78
Coefficient of target *T* (kg per t)	47.8	22.9	43.6
Coefficient of target *T* (kg per q)	4.78	2.29	4.36
Coefficient of soil test value	0.34	1.34	0.38
Coefficient of FYM nutrient (elemental)	0.64	0.82	0.68

The coefficients of P_2O_5 and K_2O include the conversion factors 2.29 and 1.21.

3.3 Ready reckoners, FYM substitution and domain of applicability

Fig. 4a–f shows the prescribed dose across the soil test range for targets of 2.5–4.5 t ha^{-1}, with and without FYM. FYM at 12.5 t ha^{-1} (24% moisture; 0.66, 0.32 and 0.54% N, P and K on a dry-weight basis) credits 40, 25 and 35 kg ha^{-1} of N, P_2O_5 and K_2O and 6.25 t ha^{-1} half of that. At the reference soil (260:22:280 kg ha^{-1} of $KMnO_4$-N, Olsen-P and NH_4OAc-K; Table 4a, Fig. 4g–i) the realised reduction with 12.5 t FYM was 46, 51 and 30% for N, 62, 43 and 18% for P_2O_5 and 35, 67 and 30% for K_2O at targets of 3.0, 3.5 and 4.0 t ha^{-1}. The reduction was largest at low targets and fell to zero where both doses were capped. Critical soil test values rose with the target and fell with FYM (Table 4b); at 3.0 t ha^{-1} they were 426, 51 and 340 kg ha^{-1} of $KMnO_4$-N, Olsen-P and NH_4OAc-K with NPK alone and 306, 33 and 249 with 12.5 t FYM.

Only part of each nomogram lies inside the calibrated range (Fig. 4, unshaded area; Fig. 1d). The soil test values of the validation farms fall inside the range for $KMnO_4$-N (241 and 249 against 198–250 kg ha^{-1}) and Olsen-P (28.5 and 29.9 against 18.2–37.4 kg ha^{-1}) but above it for NH_4OAc-K (294 and 290 against 191–255 kg ha^{-1}), so the K_2O doses at those farms are extrapolations. The critical values for N and K lie far outside the range and indicate the size of the IPNS effect (about 120 kg $KMnO_4$-N, 18 kg Olsen-P and 90 kg NH_4OAc-K lower with 12.5 t FYM) rather than thresholds.


(a)
N dose
(b)
P_2O_5 dose
(c)
K_2O dose
T
A
P
Yield target (t ha^{-1})
(d)
N dose
(e)
P_2O_5 dose
(f)
K_2O dose
$KMnO_4$-N (kg ha^{-1})
Olsen-P (kg ha^{-1})
NH_4OAc-K (kg ha^{-1})
(g)
(h)
(i)
Dose (kg ha^{-1})
-46%
-51%
-30%
-62%
-43%
-18%
-35%
-67%
-30%
Yield target (t ha^{-1})
Dose (kg ha^{-1})
Dose (kg ha^{-1})
FYM (t ha^{-1})
0
6.25
12.5

282

Fig. 4. Prescription nomograms and FYM substitution. (a–c) Doses of N, P_2O_5 and K_2O for NPK alone and (d–f) with 12.5 t FYM ha^{-1} as functions of soil test value and yield target. Colours give the dose after the maintenance and maximum limits, dashed lines mark the limits, pale areas lie outside the calibrated range, dotted vertical lines mark the sites (T, Thoppupatti; A, Ayyakannur; P, Palayam) and symbols in a–c mark the targets tested at Ayyakannur (circles) and Palayam (triangles). (g–i) Doses at the reference soil with NPK alone and with 6.25 or 12.5 t FYM ha^{-1}; the percentage above each group is the reduction achieved with 12.5 t FYM; * maintenance dose, ** cap.

Table 4a. Fertiliser doses (N:P_2O_5:K_2O, kg ha^{-1}) prescribed at a reference soil test value of 260:22:280 kg ha^{-1} ($KMnO_4$-N, Olsen-P, NH_4OAc-K).

Yield target (t ha^{-1})	NPK alone	NPK + FYM 6.25 t ha^{-1}	NPK + FYM 12.5 t ha^{-1}
3.0	56:39:23	36:27:15*	30*:15*:15*
3.5	80:45**:45	60:38:27	39:26:15*
4.0	90**:45**:45**	83:45**:45**	63:37:32

* Maintenance dose (50% of the blanket dose). ** Maximum dose (150% of the blanket dose).

Table 4b. Critical soil test values ($KMnO_4$-N / Olsen-P / NH_4OAc-K, kg ha^{-1}) at which the calculated dose is zero.

Yield target (t ha^{-1})	NPK alone	+ FYM 6.25 t ha^{-1}	+ FYM 12.5 t ha^{-1}
3.0	426 / 51 / 340	366 / 42 / 294	306 / 33 / 249
3.5	497 / 60 / 397	437 / 50 / 351	377 / 41 / 305
4.0	568 / 68 / 454	508 / 59 / 408	448 / 50 / 362

Values above 250 kg ha^{-1} of $KMnO_4$-N, 37.4 kg ha^{-1} of Olsen-P or 255 kg ha^{-1} of NH_4OAc-K lie outside the calibrated range.

3.4 Validation: accuracy of the prescriptions

All twelve target-by-farm combinations were achieved within ±10%: 91.3–103.9% of the target, with a mean of 97.0%, a mean bias of −113 kg ha^{-1} and an RMSE of 170 kg ha^{-1} (Table 5, Fig. 5a,b). Systematic error accounted for 44% of the mean

squared error. STCR-IPNS achieved 99.0% on average (94.8–103.9%; bias −43 kg ha^{-1}; RMSE 116 kg ha^{-1}) and STCR-NPK alone 95.0% (91.3–99.0%; bias −183 kg ha^{-1}; RMSE 211 kg ha^{-1}). IPNS exceeded NPK alone in all six target-by-farm pairs, by 3.5–4.9 percentage points. Achievement fell as the target rose in both approaches. Across the twelve points, observed yield = 548 + 791 × target (t ha^{-1}) + 140 × IPNS (R^2 = 0.96; 95% confidence intervals 672–910 for the slope and 43–237 kg ha^{-1} for the IPNS term), so each additional tonne of target delivered 0.79 t of extra yield and IPNS added 140 kg ha^{-1} at equal target. Ayyakannur reached 98.8% of the targets on average (bias −50 kg ha^{-1}) and Palayam 95.2% (bias −176 kg ha^{-1}).

Two treatments did not test the equations alone (Fig. 5c). For STCR-NPK 4.0 t ha^{-1} the equations called for 225 kg ha^{-1} of N + P_2O_5 + K_2O at Ayyakannur (110:53:61) and 222 kg ha^{-1} at Palayam (107:51:63), but the cap limited the applied dose to 180 kg ha^{-1} (90:45:45), 80–81% of the prescription and 93.9% and 91.3% of the target were reached. For STCR-IPNS 3.0 t ha^{-1} all three calculated doses fell below the maintenance floor (the K_2O dose was negative at both farms), so 30:15:15 was applied and 103.9% and 99.4% of the target were obtained. At 3.5 t ha^{-1} only the K_2O dose of IPNS was floored.

Table 5. Accuracy of the twelve STCR prescriptions (two farms); the dose limit that applied is stated for each target.

Prescription	n	Dose limit applied	Achievement, mean (range, %)	Bias (kg ha^{-1})	RMSE (kg ha^{-1})	MAPE (%)
All prescriptions	12	–	97.0 (91.3–103.9)	-113	170	3.9
STCR-IPNS (all)	6	–	99.0 (94.8–103.9)	-43	116	2.8
STCR-NPK (all)	6	–	95.0 (91.3–99.0)	-183	211	5.0
STCR-NPK-3.0	2	none	97.3 (95.6–99.0)	-81	96	2.7
STCR-NPK-3.5	2	none	95.1 (93.2–97.1)	-170	183	4.9
STCR-NPK-4.0	2	cap: N, P_2O_5, K_2O	92.6 (91.3–93.9)	-297	302	7.4

Prescription	n	Dose limit applied	Achievement, mean (range, %)	Bias (kg ha^{-1})	RMSE (kg ha^{-1})	MAPE (%)
STCR-IPNS-3.0	2	floor: N, P_2O_5, K_2O	101.7 (99.4–103.9)	50	84	2.2
STCR-IPNS-3.5	2	floor: K_2O	99.2 (96.9–101.5)	-28	85	2.3
STCR-IPNS-4.0	2	none	96.2 (94.8–97.7)	-151	162	3.8

Bias, mean of (observed − target); RMSE, root mean square error; MAPE, mean absolute percentage error. Targets 3.0, 3.5 and 4.0 t ha^{-1}.

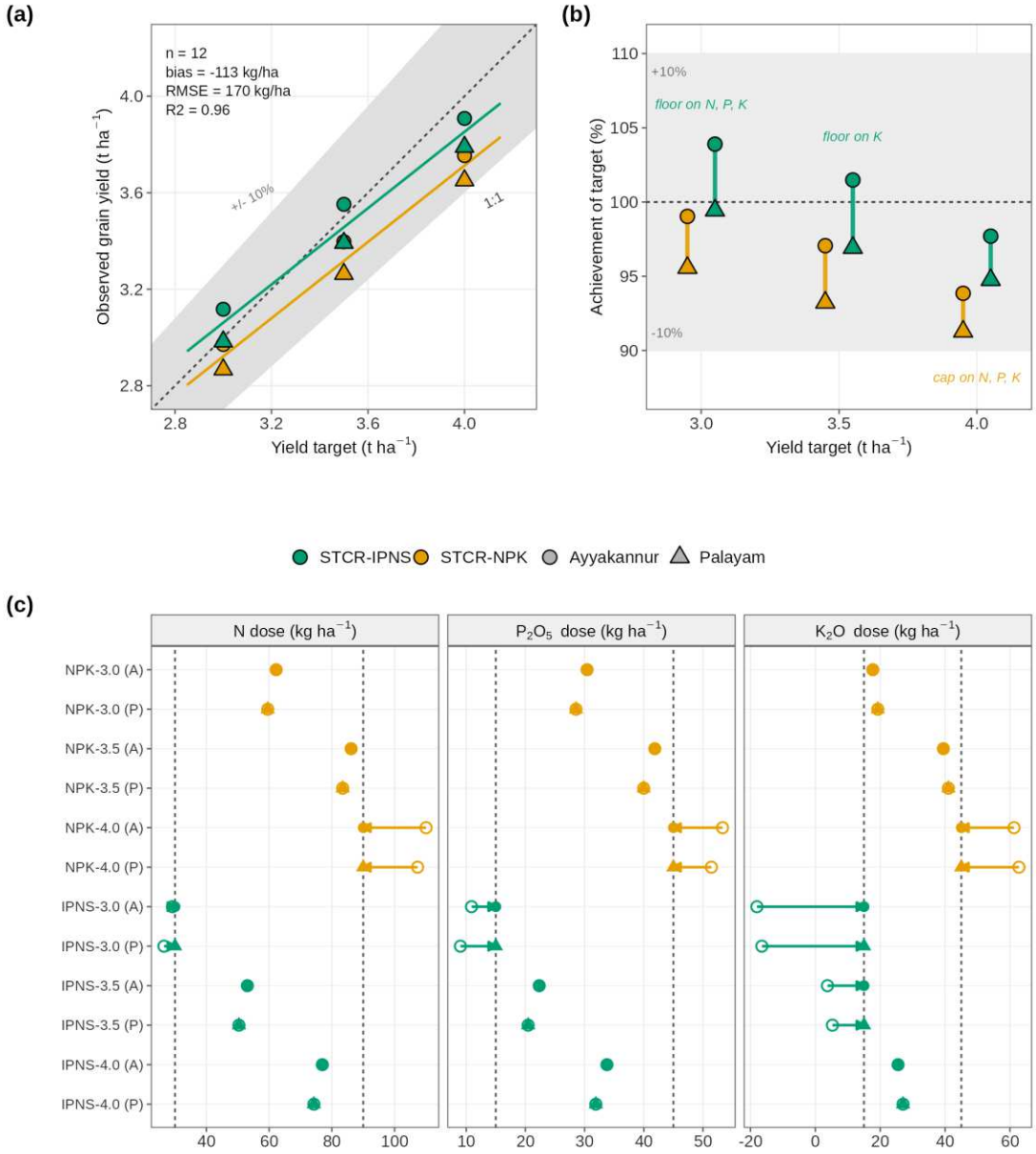


Fig. 5. Accuracy of the prescriptions. (a) Observed yield against yield target (dashed line, 1:1; grey band, ±10%; lines, fitted yield = 548 + 791 × target + 140 × IPNS). (b) Achievement of the target by approach and farm. (c) Dose from the equations (open circles) and dose after the maintenance and maximum limits (filled symbols) for each prescription at Ayyakannur (A) and Palayam (P); dashed vertical lines mark 50% and 150% of the blanket dose.

3.5 Yield, efficiency and economics

Grain yield differed among treatments (Table 6, Fig. 6a). STCR-IPNS for 4.0 t ha^{-1} gave the highest pooled yield (3849 kg ha^{-1}): 39.0, 17.1 and 57.0% above blanket

(2770), blanket plus FYM (3287) and farmers' practice (2451), 93.9% above the absolute control (1985) and 4.0% above STCR-NPK for 4.0 t ha^{-1} (3703). At equal targets STCR-IPNS out-yielded STCR-NPK by 4.0–4.5% (different letters in Table 6) with 46% (3.0 and 3.5 t ha^{-1}) and 18% (4.0 t ha^{-1}) less N + P_2O_5 + K_2O (Fig. 7). Uptake of N, P and K at equal target was 2.5–4.7%, 6.0–7.1% and 3.0–7.7% higher under IPNS and BCR 1.1–2.4% higher. FYM added to the blanket dose raised yield by 18.6%.

The response ratio per kg of fertiliser (RR_F) was 12.7–17.8 kg kg^{-1} for STCR-IPNS against 8.1–9.5 for STCR-NPK, 6.5 for blanket and 5.8 for farmers' practice (Fig. 6b). When the fertiliser equivalent of FYM entered the denominator (RR_T), IPNS values fell to 7.2–8.4 and were no longer higher than those of STCR-NPK (8.1–9.5), except at 3.5 t ha^{-1} (8.4 against 8.1). The benefit–cost ratio rose from 1.10 (control), 1.44 (farmers' practice) and 1.54 (blanket) to 1.90 (STCR-NPK 4.0) and 1.94 (STCR-IPNS 4.0) (Fig. 6c).

Table 6. Validation of the prescriptions on two farms (Ayyakannur / Palayam): applied N:P_2O_5:K_2O (kg ha^{-1}), pooled grain yield (kg ha^{-1}; letters from the ANOVA as reported, means with a common letter do not differ at P < 0.05), achievement of the target, response ratios and benefit–cost ratio.

Treatment	Applied N:P_2O_5:K_2O	FYM	Yield	Achievement (%)	RR_F	RR_T	BCR
T1 Blanket (RDF)	60:30:30 / 60:30:30	0	2770 h	-	6.54	6.54	1.54
T2 Blanket + FYM	60:30:30 / 60:30:30	12.5	3287 de	-	10.85	6.25	1.74
T3 STCR-NPK 3.0	65:31:19 / 59:29:21	0	2919 g	99.0 / 95.6 / 97.3	8.35	8.35	1.75
T4 STCR-NPK 3.5	85:42:41 / 83:40:42	0	3330 d	97.1 / 93.2 / 95.1	8.08	8.08	1.82
T5 STCR-NPK 4.0	90:45:45 / 90:45:45 (cap)	0	3703 b	93.9 / 91.3 / 92.6	9.54	9.54	1.90
T6 STCR-IPNS 3.0	30:15:15 / 30:15:15 (floor)	12.5	3050 f	103.9 / 99.4 / 101.7	17.75	7.18	1.78

Treatment	Applied N:P_2O_5:K_2O	FYM	Yield	Achievement (%)	RR_F	RR_T	BCR
T7 STCR-IPNS 3.5	52:23:16 / 50:21:17	12.5	3472 c	101.5 / 96.9 / 99.2	16.62	8.36	1.84
T8 STCR-IPNS 4.0	76:34:38 / 74:33:39	12.5	3849 a	97.7 / 94.8 / 96.2	12.68	7.92	1.94
T9 Farmers' practice	40:20:20 / 40:20:20	0	2451 i	-	5.83	5.83	1.44
T10 Absolute control	0:0:0 / 0:0:0	0	1985 j	-	-	-	1.10

Achievement is shown for Ayyakannur / Palayam / pooled. FYM in t ha^{-1}. RR_F, response per kg of fertiliser N + P_2O_5 + K_2O applied; RR_T, response per kg of fertiliser plus the fertiliser equivalent of FYM (88 kg ha^{-1}). BCR is the mean of the two farms.

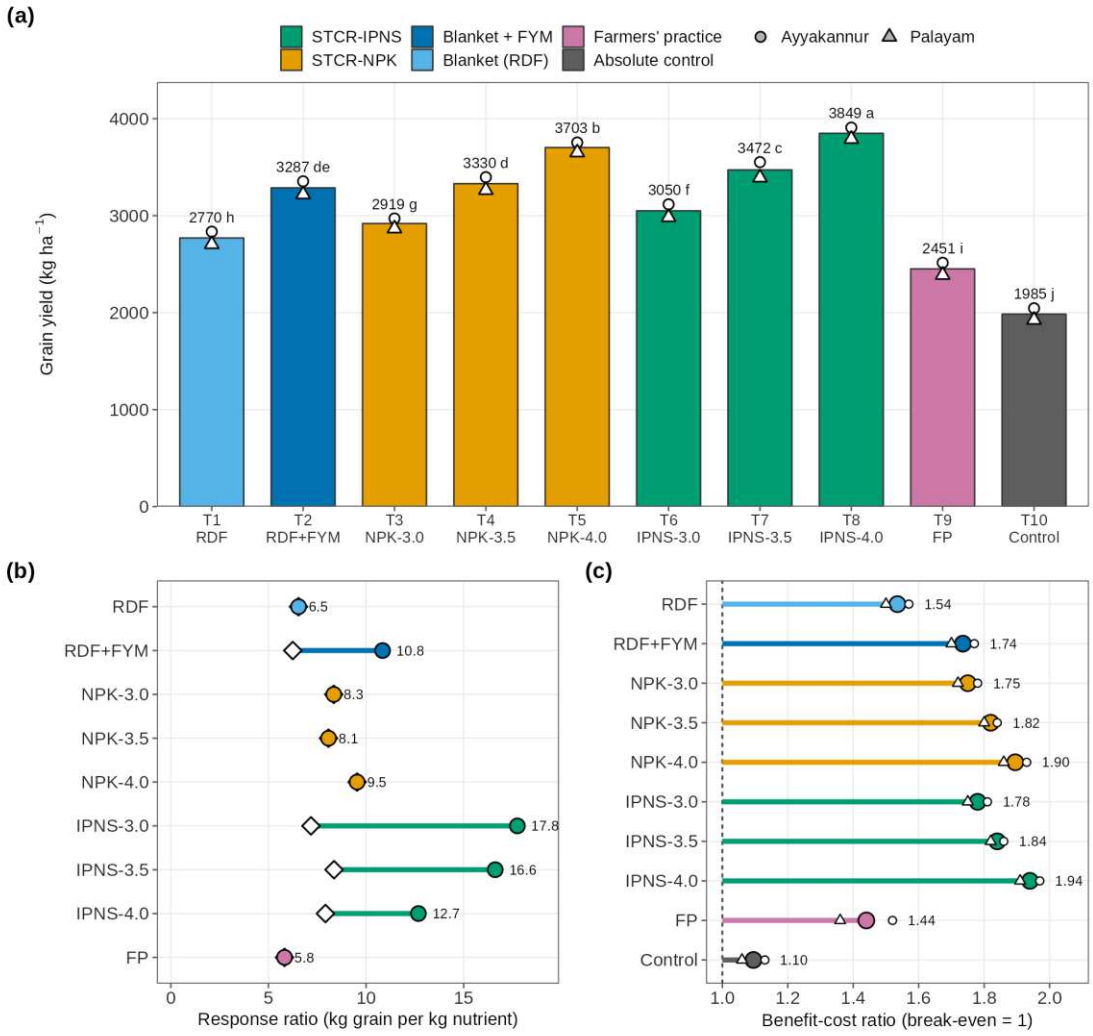


Fig. 6. Yield, response ratio and benefit–cost ratio. (a) Pooled grain yield (bars, mean of two farms; symbols, individual farms; letters from the ANOVA as reported). (b) Response ratio per kg of fertiliser applied (RR_F, filled circles) and per kg of fertiliser plus the FYM equivalent (RR_T, open diamonds). (c) Benefit–cost ratio (large symbols, mean of farms; small symbols, single farms; dashed line, break-even).

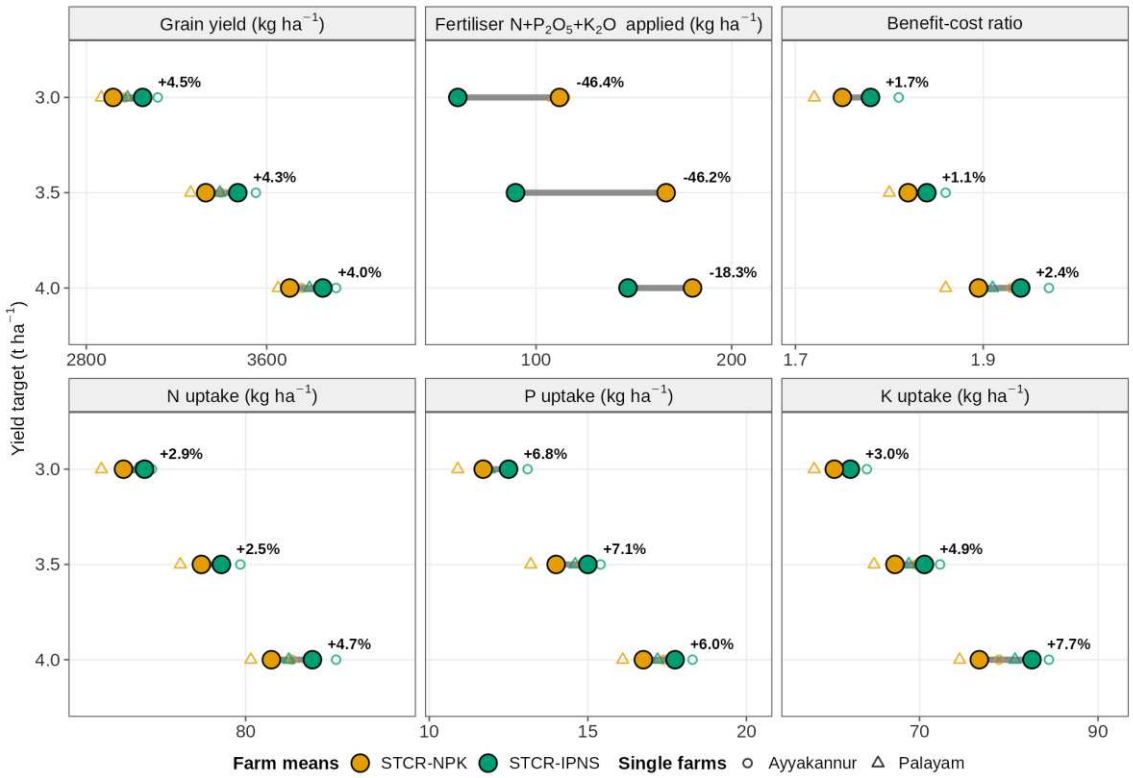


Fig. 7. Matched-target comparison of STCR-NPK and STCR-IPNS. Large circles are means of the two farms, small open symbols the single farms (circles, Ayyakannur; triangles, Palayam) and the labels give the difference of IPNS relative to NPK alone at the same yield target.

3.6 Nutrient uptake and stoichiometry

N, P and K uptake rose from 46.7, 6.3 and 47.3 kg ha^{-1} in the absolute control to 86.4, 17.8 and 82.6 kg ha^{-1} under STCR-IPNS for 4.0 t ha^{-1} (Table 7). Uptake per tonne of grain exceeded the calibrated N requirement by 8% on average (21.6–24.4 kg N t^{-1} against 21.1) and fell 3% short of the calibrated K_2O requirement (23.6–29.7 kg against 26.0). P_2O_5 uptake per tonne rose from 7.3 kg in the control to 8.4–10.7 kg in fertilised plots, 24% above the calibrated 7.5 kg on average (Fig. 8b). The share of P_2O_5 in total N + P_2O_5 + K_2O uptake increased from 12.2% in the control to 14.7–18.1% in fertilised plots, whereas the share of K_2O fell from 48.3% to 43.0–44.9% (Fig. 8a). The control lay closest to the calibrated proportions of 38.6:13.7:47.6.

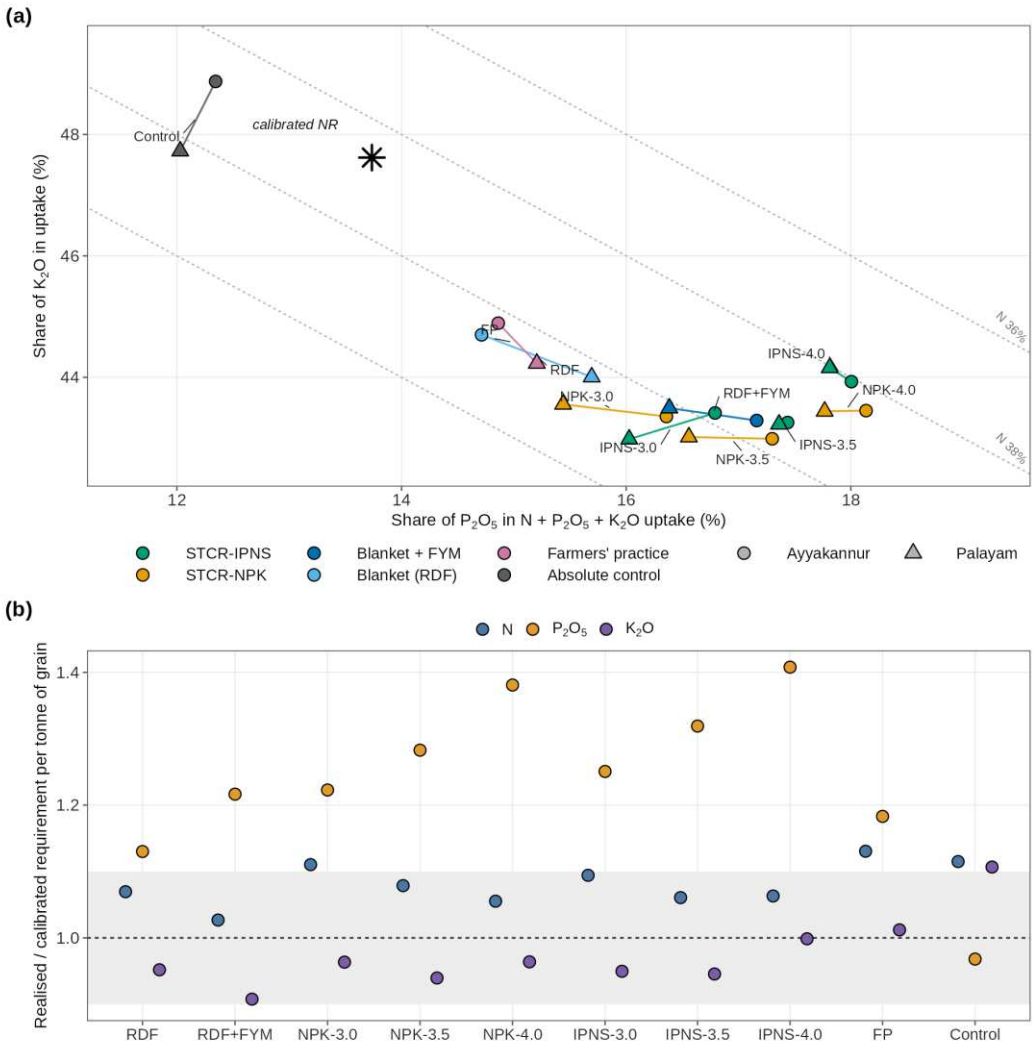


Fig. 8. Uptake stoichiometry. (a) Shares of P_2O_5 and K_2O in total N + P_2O_5 + K_2O uptake; the N share follows from the diagonals, lines join the two farms of each treatment and the star marks the calibrated requirement ratio (38.6:13.7:47.6). (b) Uptake per tonne of grain relative to the calibrated nutrient requirement (points, mean of two farms; bars, range between farms; grey band, ±10%).

3.7 Growth traits and multivariate structure

Plant height, tillers m^{-2}, fingers per earhead, earhead weight, SPAD reading and leaf N were highest under STCR-IPNS for 4.0 t ha^{-1} and lowest in the absolute control at both farms (Table 7) and STCR-IPNS exceeded STCR-NPK at the same target for every trait. LAI and test weight showed the same order but were not significant.

Table 7. Growth, yield attributes and nutrient uptake at harvest, mean of the two farms.

Treatment	Plant height (cm)	Tillers (m^{-2})	Fingers per earhead	Earhead weight (g)	SPAD	Leaf N (mg g^{-1})	N uptake	P uptake	K uptake
T1	81.5	92.5	8.5	8.8	24.0	16.5	62.6	10.3	56.7
T2	84.0	98.9	9.3	9.7	25.5	18.5	71.2	13.1	64.1
T3	84.2	94.6	8.7	8.9	24.6	17.4	68.4	11.7	60.5
T4	87.6	102.2	9.5	10.2	26.2	18.9	75.8	14.0	67.3
T5	90.8	111.1	10.1	11.5	28.9	20.2	82.5	16.8	76.7
T6	86.1	97.6	8.9	9.4	25.2	18.1	70.4	12.5	62.3
T7	89.1	107.8	9.9	10.9	27.7	19.8	77.7	15.0	70.6
T8	91.1	116.7	11.0	12.5	30.9	20.8	86.4	17.8	82.6
T9	79.4	87.5	7.8	8.5	23.6	15.8	58.5	9.5	53.4
T10	69.0	78.3	6.4	7.2	23.1	14.1	46.7	6.3	47.3

Uptake in kg ha^{-1} (P and K as elemental P and K). Treatments as in Table 6.

The first principal component explained 96.7% of the variance in the 15 traits (eigenvalue 14.5) and was the only component above the parallel-analysis threshold (3.3); PC2 and PC3 explained 1.9 and 0.6%, below their thresholds of 2.6 and 2.2 (Fig. 9a). All traits correlated with PC1 at 0.94–1.00 and SPAD reading was the trait most associated with PC2 (r = 0.34). Scores ran along PC1 from −7.4 (control) to +6.1 (STCR-IPNS 4.0) in the order control < farmers' practice < blanket < STCR-NPK 3.0 < STCR-IPNS 3.0 ≈ blanket plus FYM < STCR-NPK 3.5 < STCR-IPNS 3.5 < STCR-NPK 4.0 < STCR-IPNS 4.0 (Fig. 9b) and the scores at the two farms agreed almost exactly (r = 0.9999). STCR-IPNS 3.0 scored like blanket plus FYM with half the fertiliser (60 against 120 kg ha^{-1}) and STCR-IPNS 3.5 scored above STCR-NPK 3.5 with 46% less.

Projected as supplementary variables, BCR and fertiliser applied correlated with PC1 at 0.93 and 0.76, RR_T at 0.70 and RR_F at 0.49 (Fig. 9c). Plotted against purchased fertiliser, the six fertiliser-only treatments followed a smooth quadratic response of PC1 (R^2 = 0.96) and the four FYM-treated treatments lay above that curve by 1.9 PC1 units

(blanket plus FYM, 120 kg ha^{-1}), 5.3 (STCR-IPNS 3.0, 60 kg ha^{-1}), 6.4 (3.5 t ha^{-1}, 90 kg ha^{-1}) and 5.6 (4.0 t ha^{-1}, 147 kg ha^{-1}) (Fig. 9d). Read against the fitted curve, STCR-IPNS 3.0 (60 kg ha^{-1} applied) and STCR-IPNS 3.5 (90 kg ha^{-1}) corresponded to 141 and 172 kg ha^{-1} of fertiliser alone, so FYM replaced about 81 and 83 kg ha^{-1} of fertiliser, whereas blanket plus FYM (120 kg ha^{-1}) corresponded to 144 kg ha^{-1}, a replacement of about 24 kg ha^{-1}; STCR-IPNS 4.0 lies beyond the tested fertiliser range. Average-linkage clustering (Fig. 10) separated the control; STCR-NPK 4.0 together with STCR-IPNS 3.5 and 4.0; an intermediate group of blanket plus FYM, STCR-NPK 3.5 and STCR-IPNS 3.0; and a low group of farmers' practice, blanket and STCR-NPK 3.0.

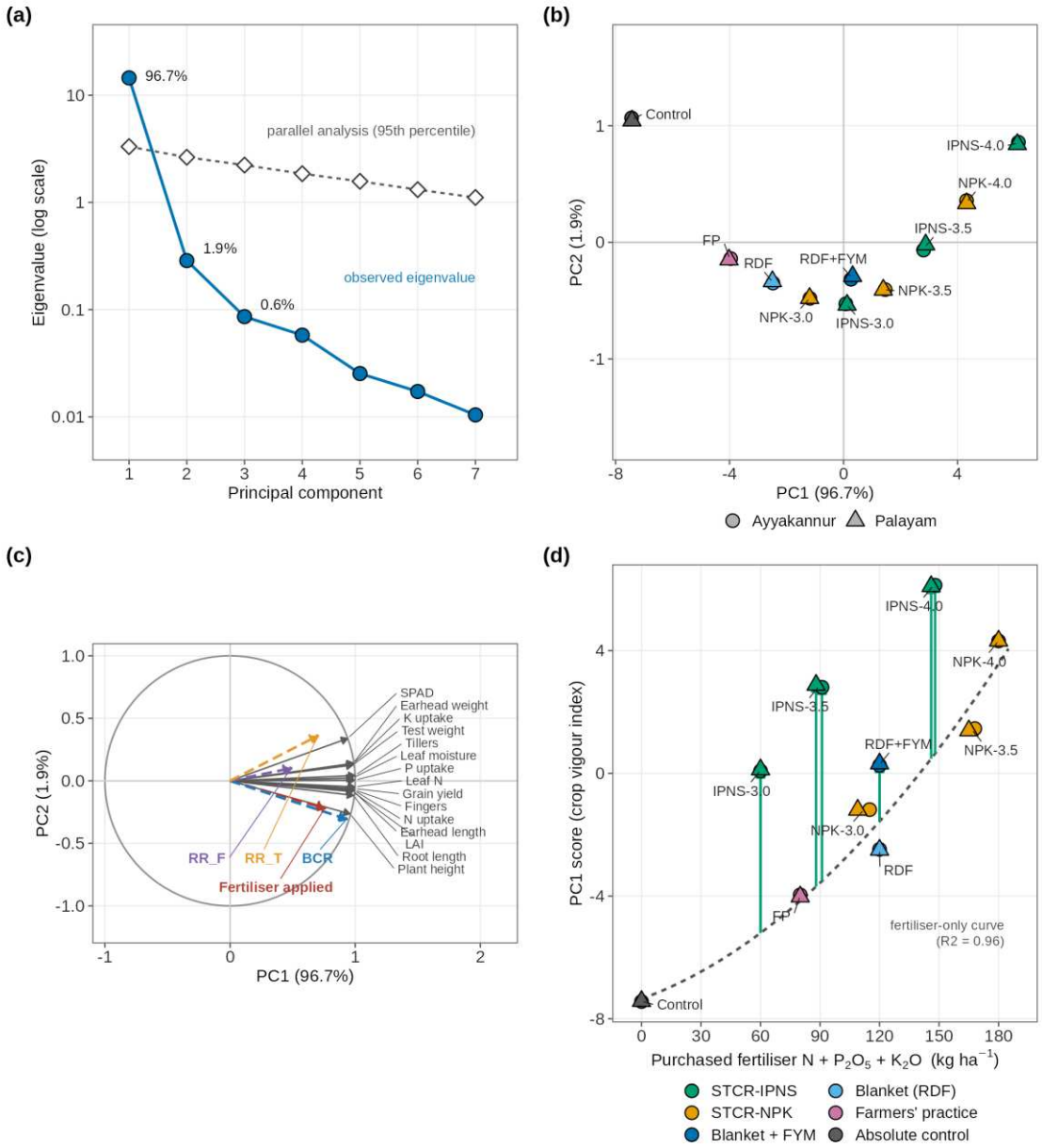


Fig. 9. Principal component analysis of 15 traits (within-farm standardised, n = 20 treatment-by-farm means). (a) Eigenvalues against the parallel-analysis threshold (log scale). (b) Treatment scores on PC1 and PC2; lines join the two farms. (c) Correlation circle with the 15 active variables (solid) and four supplementary variables (dashed). (d) PC1 score against purchased fertiliser; the dashed curve is the quadratic fit to the fertiliser-only treatments and the arrows show the gain of the FYM-treated treatments over that curve.

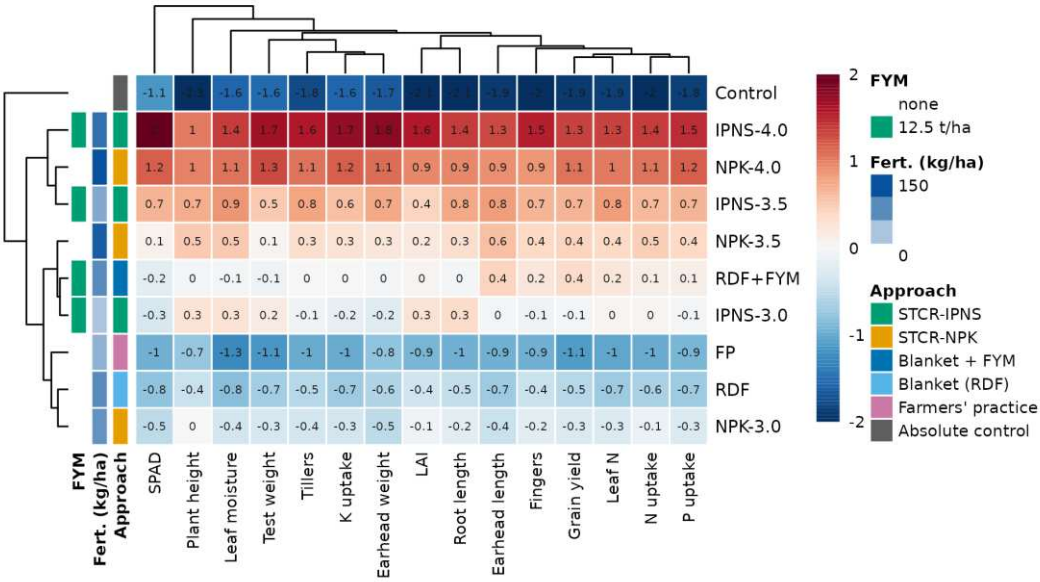


Fig. 10. Clustered heat map of standardised treatment profiles (z-scores within farm, mean of the two farms) with average-linkage dendrograms. Annotation bars give the approach, FYM and fertiliser applied.

4. Discussion

4.1 Basic parameters in context

The requirement of finger millet on this *Rhodustalf* (21.1 kg N, 7.5 kg P_2O_5 and 26.0 kg K_2O per tonne of grain) is lower for N and P_2O_5 than the 28.1 kg N and 13.3 kg P_2O_5 per tonne reported for pearl millet var. CO 10 on an *Inceptisol* and similar for K_2O (25.3 kg; Ravikiran *et al*., 2018). The contributions of fertiliser N (44.16 against 45.44%) and FYM-N (28.47 against 27.55%) are close in the two crops, whereas soil N contributes less in finger millet (14.86 against 26.36%) and the P_2O_5 contributions of soil, fertiliser and FYM are 50–74% of those in pearl millet (19.19, 32.79 and 11.77 against 38.51, 44.14 and 16.04%). FYM-P contributes least of the three nutrients in both crops. FYM at 12.5 t ha^{-1} (21% moisture; 0.64, 0.27 and 0.46% N, P and K) saved 38, 22 and 25 kg ha^{-1} of N, P_2O_5 and K_2O in pearl millet (Ravikiran *et al*., 2018), against credits of 40, 25 and 35 kg ha^{-1} here.

On *Mollisols* of northern India, FYM at 5 t ha^{-1} contributed 21.84, 4.56 and 56.84% of N, P and K uptake and cut the mineral doses by 24.4, 18.8 and 45.2%

(Ayushi *et al*., 2022). The order of the three contributions differs from ours (28.47, 11.77 and 33.78%), as expected for a different soil and manure, but FYM-P is again the weakest. In Karnataka, an integrated prescription for 40 q ha^{-1} overshot the target by 5.0 and 6.6% at two locations (42.00 and 42.65 q ha^{-1}; Murthy *et al*., 2023) and on the Palaviduthi series an FYM-adjusted greengram prescription reached 105.8% of its target (Abhirami *et al*., 2026). The finger millet prescriptions of this study reached 94.8–103.9%, so accuracy of a comparable order was obtained with a calibration done on a single soil series.

4.2 Accuracy and the role of the dose limits

All prescriptions met the ±10% criterion, but the errors were systematic. The mean bias of −113 kg ha^{-1} contributed 44% of the mean squared error, the slope of observed on target was 0.79 and not 1 and achievement fell as the target rose (Table 5, Fig. 5a,b). Part of the shortfall at the high target follows from the dose limit. The cap held the dose of STCR-NPK 4.0 t ha^{-1} to 80–81% of the prescription and the treatment reached 93.9 and 91.3% of the target, the lowest values of the trial. At the other end, the floor raised the IPNS 3.0 t ha^{-1} dose above the calculated value, because the K_2O dose was negative and all three doses fell below 50% of the blanket dose and the treatment exceeded its target at Ayyakannur (103.9%). Accuracy at the extremes of the target range therefore depends on the limits as much as on the equations and a validation report should state which treatments were limited (Fig. 5c). The realised N requirement per tonne of grain (21.6–24.4 kg) exceeded the calibrated 21.1 kg by 8% on average. An underestimated requirement lowers the dose and the yield, which agrees in sign with the negative bias; confirming it needs further seasons.

The equations were derived on one site and one season and the validation farms differ from the calibration site in their soil test values. Soil K at both validation farms (294 and 290 kg ha^{-1}) lay above the calibrated range (191–255 kg ha^{-1}; Fig. 1d, Fig. 4), so the K_2O term was extrapolated at both farms. The K_2O doses applied were 15–45 kg ha^{-1} and the validation does not test the K equation above 255 kg ha^{-1}. The lower achievement at Palayam (95.2%) than at Ayyakannur (98.8%) coincided with a later sowing date (19 January against 10 December); a seasonal effect cannot be separated from a farm effect with two sites.

4.3 Efficiency and economics of IPNS

The efficiency ranking of IPNS depends on how the nutrients in FYM are counted. Per kg of purchased fertiliser, IPNS returned 12.7–17.8 kg of grain, up to twice the response of STCR-NPK (8.1–9.5). When the 88 kg ha^{-1} fertiliser equivalent of 12.5 t FYM entered the denominator, the IPNS values fell to 7.2–8.4 and no longer exceeded those of STCR-NPK except at 3.5 t ha^{-1}. The advantage of IPNS therefore lies in the manure's nutrients and not in a more efficient use of a common nutrient pool. The agronomic gains remain: 4.0–4.5% more grain at equal target and 18–46% less purchased fertiliser. The benefit–cost ratio rose with the target in both approaches (1.78–1.94 for IPNS and 1.75–1.90 for NPK alone) and it correlated more strongly with PC1 ($r = 0.93$) than RR_F did ($r = 0.49$), so profit in this trial followed crop vigour and yield, not fertiliser-use efficiency. The BCR depends on the price assigned to FYM. The response of the same series to FYM-adjusted STCR-IPNS in greengram showed the same direction for yield, response ratio and benefit–cost ratio (Abhirami *et al*., 2026).

4.4 Uptake stoichiometry

The calibrated requirement ratio (38.6:13.7:47.6 for N:P_2O_5:K_2O) was matched most closely by the control. Fertilised plots took up proportionally more P and less K (Fig. 8a) and P_2O_5 uptake per tonne of grain was 24% above the calibrated requirement on average and up to 41% above it under the high targets (Fig. 8b). This pattern may reflect the higher Olsen-P of the validation farms (28.5 and 29.9 kg ha^{-1} against 21.3 kg ha^{-1} at the calibration site). It does not affect the accuracy of the yield prescriptions, because the P equation is dominated by the target and soil terms, but it indicates that the P dose can be tested for savings on soils above the calibrated Olsen-P range.

4.5 Multivariate consistency

The first component accounted for 96.7% of the variance because the 15 traits respond together to nutrient supply. The PCA therefore confirms the ranking and adds no independent evidence of treatment differences. Its value lies in placing different traits on a common scale. The quadratic response of PC1 to purchased fertiliser gives a benchmark against which FYM-treated treatments can be read: STCR-IPNS 3.0 and 3.5 stood at the level reached by 141 and 172 kg ha^{-1} of fertiliser alone, a replacement of about 81 and 83 kg ha^{-1}, which is close to the 88 kg ha^{-1} fertiliser equivalent

calculated from the nutrient credits. Blanket plus FYM replaced only about 24 kg ha^{-1}, which indicates that FYM added to a full blanket dose is less productive per unit than FYM that substitutes for fertiliser. PCA has been used in STCR research to derive soil quality indices from enzyme and microbial data (Murthy *et al*., 2024; Abhirami *et al*., 2026). Here it summarises crop traits and a soil-quality extension would require biological data that were not collected in Phase III. The analysis rests on 20 treatment-by-farm means from two farms, which are not independent replicates.

4.6 Applicability and limitations

The equations apply to finger millet cv. ATL 1 on *Typic Rhodustalf*s within the calibrated range of $KMnO_4$-N (198–250 kg ha^{-1}), Olsen-P (18.2–37.4 kg ha^{-1}) and NH_4OAc-K (191–255 kg ha^{-1}). Outside it, the ready reckoners are extrapolations. The FYM credit assumes a manure of the composition used here (24% moisture; 0.54–0.66% N, 0.25–0.32% P and 0.54–0.55% K on a dry-weight basis); for a different manure *ON*, *OP* and *OK* must be recomputed with Eqs. 10–12. The validation covers one season, two farms and one soil series and it shows that the equations can hit a target within ±10% in this setting; it does not establish the error distribution under other seasons or soils. Weather records, the costing behind the BCR and the exact positions of the validation farms are needed to complete the dataset. A spatial extension is straightforward: Eqs. 10–12 can be applied to interpolated soil test layers to give prescription maps for a block or district, with pixels outside the calibrated range masked. The site layer supplied with this paper is the starting point for that work.

5. Conclusions

- Finger millet cv. ATL 1 on a *Typic Rhodustalf* required 21.1 kg N, 7.5 kg P_2O_5 and 26.0 kg K_2O per tonne of grain. Soil, fertiliser and FYM supplied 14.86, 44.16 and 28.47% of N uptake, 19.19, 32.79 and 11.77% of P_2O_5 uptake and 18.95, 59.75 and 33.78% of K_2O uptake and these parameters yield the prescription equations 10–12.
- FYM at 12.5 t ha^{-1} replaced about 40 kg N, 25 kg P_2O_5 and 35 kg K_2O, which cut the prescribed dose at the reference soil by 18–67% depending on nutrient and target.

- On two independent farms the prescriptions reached 91.3–103.9% of the target (bias −113 kg ha^{-1}; RMSE 170 kg ha^{-1}), 99.0% on average for STCR-IPNS and 95.0% for STCR-NPK. The maximum dose limited the 4.0 t ha^{-1} NPK-alone prescription and the maintenance dose limited the 3.0 t ha^{-1} IPNS prescription.
- STCR-IPNS for 4.0 t ha^{-1} gave 3849 kg ha^{-1} and a benefit–cost ratio of 1.94 and at equal targets it gave 4.0–4.5% more grain than STCR-NPK with 18–46% less purchased fertiliser. Its response-ratio advantage disappeared when the nutrients in FYM were counted.
- A single principal component (96.7% of variance) ranked all treatments identically on both farms. The validation farms had soil K above the calibrated range and the equations should be used within the soil test ranges stated above until they are validated beyond them.

Declarations

Author Contributions.

B. Asan Mohamed: Conceptualization, methodology design, literature synthesis, spatial risk framework development, writing — original draft, writing — review & editing, corresponding author responsibility.

R. Santhi: Data provision from STCR-IPNS field trials, supervision of soil fertility sections, writing — review.

S. Maragatham: Data provision from nutrient management studies, review of validation experiment sections, writing — review.

M. Gopalakrishnan: Data provision from soil fertility gradient experiments, writing — review.

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Consent to publish: Not applicable.

Clinical trial number: Not applicable.

Data availability: The treatment-by-farm data supporting this study are provided in Supplementary Data S1.

Code availability: All analyses and figures can be reproduced with the R script. The R code used for the analyses and figures is provided as Supplementary Code S2.

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