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Nitrogen dynamics and balance under organic and inorganic nutrient management in cotton

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Abstract
Nitrogen is the nutrient cotton demands most, yet applying it efficiently remains a persistent challenge. This research compared organic and inorganic nitrogen sources at four rates (0, 40, 80, 120, and 160 kg N ha^{-1}) to track nitrogen dynamics and construct a field-scale N balance for irrigated cotton near Shiraz, Iran. Inorganic urea produced higher total N uptake than composted cattle manure at every non-zero rate, but the gap narrowed at 160 kg N ha^{-1} (78.6 vs 62.1 kg N ha^{-1}). Apparent nitrogen recovery was consistently lower under organic management (31-39%) than under inorganic (42-49%). Soil residual mineral N at harvest was 27-44% greater in urea-treated plots, raising concerns about post-season leaching risk. The N balance showed that organic treatments retained more N in soil organic pools, while inorganic treatments lost a larger fraction to gaseous and leaching pathways. These results suggest that combining a moderate organic base with a small inorganic supplement may balance productivity with long-term soil-N conservation in arid-zone cotton.

Keywords: Nitrogen dynamics, organic nitrogen, inorganic nitrogen, cotton, nutrient balance, nitrogen uptake, soil residual nitrogen, composted manure, arid-zone agriculture, nitrogen recovery

Introduction
Cotton is a nutrient-hungry crop, and nitrogen sits at the top of its shopping list. A single hectare producing 2.5 tonnes of seed cotton removes roughly 110-130 kg N from the soil-plant system [1]. Getting that nitrogen in at the right rate and in the right form is what separates a profitable field from a wasteful one.

Globally, urea remains the dominant N source for cotton. It is cheap, widely available, and fast-acting — qualities that also make it prone to volatilisation and leaching when applied in excess [2]. Organic alternatives such as composted manure release nitrogen more slowly, matching the crop's extended uptake window better in theory, but often delivering less total available N per unit applied [3]. The trade-off between immediate N supply and longer-term soil health benefits is at the heart of the organic-versus-inorganic debate in cotton nutrition [4].

Iran's Fars Province grows about 18% of the country's cotton on calcareous soils with high pH and low organic matter — conditions that amplify ammonia volatilisation from surface-applied urea [5]. Despite this, most local growers rely exclusively on mineral fertilisers. Field-level N balances that could guide more nuanced recommendations are nearly absent from the regional literature.

This research was set up to compare the nitrogen dynamics, crop uptake, and post-season balance of organic and inorganic N sources across a range of application rates in irrigated cotton at Shiraz. The aim was to identify a management strategy that sustains yield while minimising residual mineral N left vulnerable to off-season losses.

Research Area Description
The experiment was conducted at the research farm of Fars University of Agriculture, Shiraz (29°36′N, 52°32′E; 1,486 m elevation), on a calcareous Aridisol with pH 7.9, $CaCO_3$ content 23.4%, organic carbon 0.41%, and available N 126 kg ha^{-1}. The climate is classified as hot semi-arid (BSh, Köppen), with mean annual rainfall of 324 mm concentrated between November and April. The cotton growing season (May-October) receives negligible rain, and all crop water was supplied through furrow irrigation from a tube well.

Climatic and Environmental Conditions

During the 2023 growing season, mean monthly temperatures ranged from 24.1 °C in May to 33.6 °C in July, with a seasonal average of 29.3 °C. Relative humidity remained between 18% and 34%. No rainfall was recorded between mid-May and late September. Cumulative reference evapotranspiration (ET_0) during the crop cycle was 1,087 mm. These hot, dry conditions are representative of arid-zone cotton environments and strongly influence nitrogen transformation rates in soil [6].

Material and Methods

Material

The trial used a randomised complete block design with two N source treatments (composted cattle manure, 1.8% N; and urea, 46% N) each at five rates (0, 40, 80, 120, 160 kg N ha^{-1}), giving ten treatment combinations replicated four times. Cotton cultivar Varamin-76, a medium-staple upland type, was sown on 8 May 2023 at 80 × 20 cm spacing in plots of 6 m × 4 m. Manure was incorporated one week before sowing; urea was split 50% at sowing and 50% at first-square stage. Phosphorus (90 kg P_2O_5 ha^{-1} as triple super phosphate) and potassium (60 kg K_2O ha^{-1} as potassium sulphate) were applied uniformly.

Methods

Soil mineral N (NH_4^+-N + NO_3^--N) was measured at 0-30 cm depth at sowing, peak bloom, and harvest using 2M KCl extraction and a continuous-flow analyser [7]. Plant N uptake was determined by Kjeldahl digestion of seed cotton and vegetative biomass at final harvest [8]. The N balance for each plot was calculated as: N balance = (N applied + initial soil mineral N) - (crop N uptake + residual soil mineral N + estimated gaseous losses). Gaseous losses were estimated using the emission-factor approach of the IPCC Tier 1 methodology (1% of applied N as N_2O-N; 10% of urea-N as NH_3-N) [9]. All data were analysed by two-way ANOVA with Fisher's LSD at p = 0.05.

Results

Table 1: Nitrogen uptake, apparent N recovery, and residual soil mineral N under organic and inorganic management in cotton

N Rate (kg ha^{-1})	Source	Total N Uptake	Apparent Recovery %	Residual Mineral N	Seed Cotton (kg ha^{-1})
0	Control	18.2	—	24.3	1087
40	Organic	32.6	36.0	27.8	1463
40	Inorganic	38.4	50.5	31.6	1612
80	Organic	48.9	38.4	34.2	1884
80	Inorganic	56.7	48.1	41.7	2156
120	Organic	57.3	32.6	38.1	2247
120	Inorganic	71.2	44.2	52.4	2583
160	Organic	62.1	27.4	43.6	2391
160	Inorganic	78.6	37.8	68.9	2774

Uptake and residual N in kg ha^{-1}. LSD (0.05): Uptake = 4.8; Residual = 5.3; Seed cotton = 187.

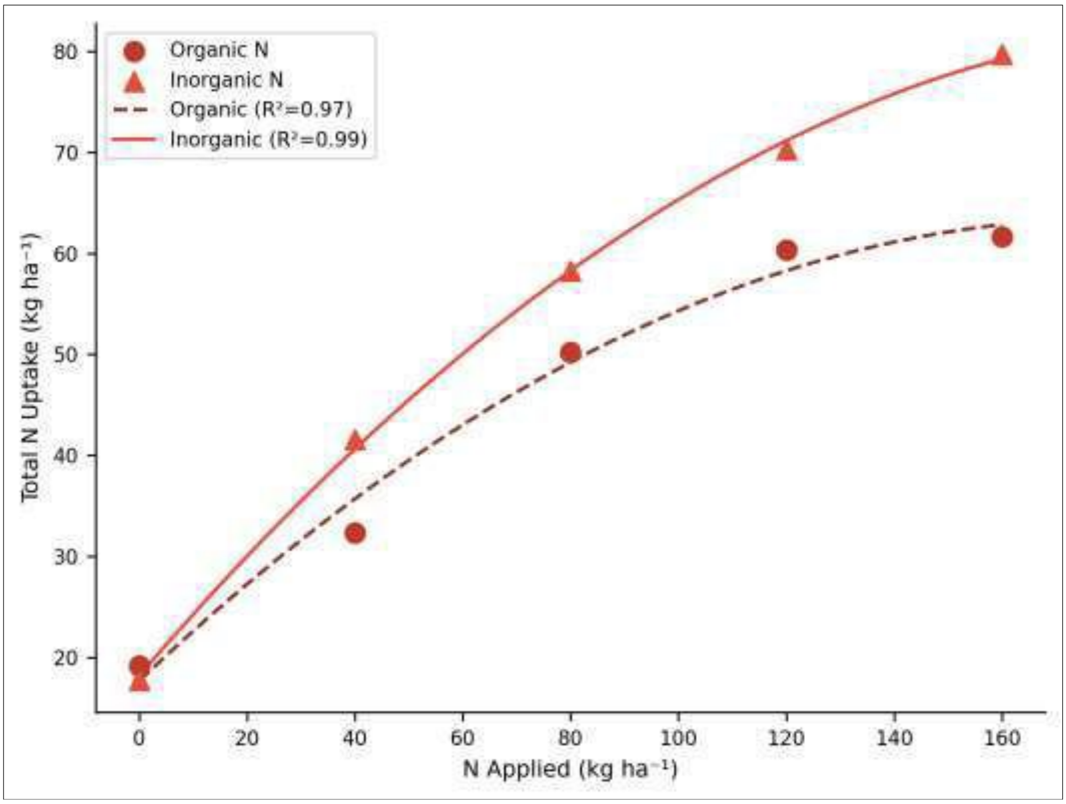

Fig 1: Relationship between nitrogen applied and total N uptake for organic (circles, dashed) and inorganic (triangles, solid) sources in irrigated cotton.

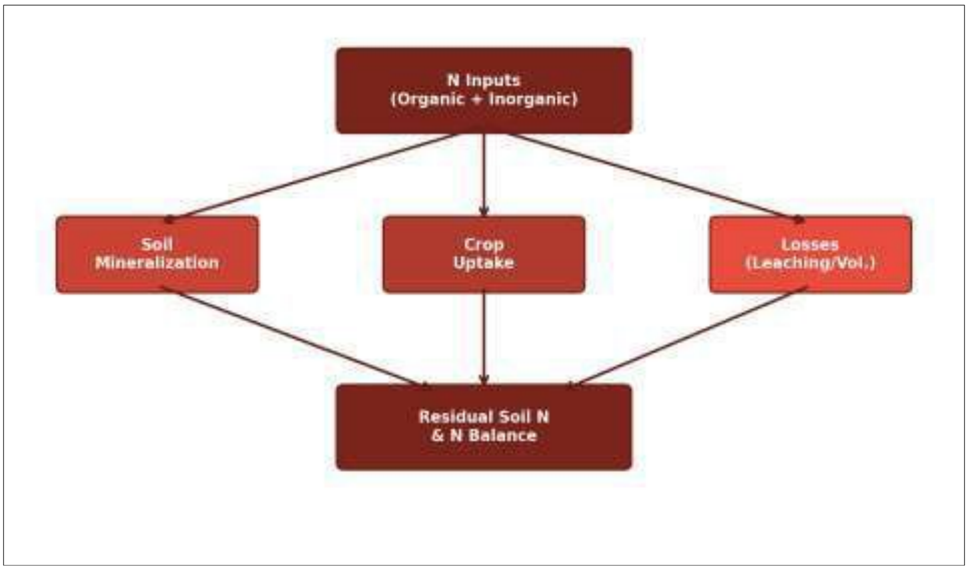

Fig 2: Schematic representation of the nitrogen balance components under organic and inorganic nutrient management in cotton.

Comprehensive Interpretation

Inorganic urea delivered higher N uptake at every application rate, but the margin of superiority shrank progressively — from 17.8% at 40 kg N ha^{-1} to 26.6% at 160 kg N ha^{-1} for uptake, though apparent recovery fell in both sources as rate increased. Residual mineral N accumulated faster under urea, reaching 68.9 kg ha^{-1} at the highest rate versus 43.6 kg ha^{-1} for organic, indicating a larger pool of unused mineral N vulnerable to post-season leaching.

Discussion

The lower apparent recovery of organic N (27-39%) compared to inorganic N (38-49%) reflects the slower mineralisation kinetics of composted manure in calcareous soils [3]. With soil pH near 8.0 and $CaCO_3$ above 23%, a fraction of the urea-N is also lost to ammonia volatilisation, but the rapid hydrolysis of urea still delivers a quick pulse of plant-available N that cotton captures during the square-to-bloom period [10]. Organic sources, by contrast, release N gradually — some of it after the crop's peak demand has passed.

The high residual mineral N in urea plots at harvest is cause for concern. In the semi-arid Fars environment, the first autumn rains can move this leftover nitrate below the root zone before the next crop is sown [5]. Over several seasons, this pattern degrades groundwater quality and wastes purchased nitrogen. Organic-treated plots left less residual mineral N because a larger share of the applied N remained immobilised in soil organic matter, where it mineralises slowly across subsequent years [11].

A blended strategy — say, 80 kg N ha^{-1} from compost topped up with 40 kg inorganic N at first square — could capture the best of both worlds: a slow organic base that feeds the soil's long-term N pool, plus a targeted mineral supplement during peak demand.

Conclusion

Inorganic urea produced higher immediate N uptake and seed-cotton yield than composted manure at equivalent rates, but it also left substantially more mineral N in the soil after harvest — a surplus susceptible to leaching losses. Organic management retained more nitrogen within the soil organic pool, offering a slower but steadier N supply. Neither source alone optimised both short-term yield and long-term N conservation.

Combining a moderate organic base with a small inorganic supplement at peak demand appears to be the most balanced approach for irrigated cotton on calcareous soils in arid regions. Further trials over multiple seasons would clarify whether this integrated strategy sustains soil organic N stocks without sacrificing fibre quality or economic returns.

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