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Balanced Nutrition Through the Application of Customized Fertilizers to Flue-Cured Virginia Tobacco

J. Poorna Bindu[a], M. Sheshu Madhav[a], M. Anuradha[a], D. Damodar Reddy[b], S. Kasturi Krishna[a], L. K. Prasad[a], C. Chandrasekhara Rao[a], Rajasekhara Rao Korada[a], and A. Jeyabal[c]

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ABSTRACT

Most tobacco farmers cultivate flue-cured Virginia (FCV) tobacco (*Nicotiana tabacum* L.) using straight fertilizers (SFs). However, they tend to avoid using potassium fertilizers due to their high cost, resulting in imbalanced nutrition and suboptimal nutrient use efficiency. This study aimed to assess the effects of customized NPK fertilizers grades alone and in combination with micronutrient products, namely Tracs Sure and Akre Shield, on soil properties and FCV tobacco yield, leaf quality, nutrient uptake, and nutrient use efficiency. Field experiments were conducted under northern light soils (NLS, irrigated) and southern light soils (SLS, rainfed). A randomized complete block design with nine treatments – unfertilized cropped control, SFs, and various combinations of Customized Fertilzers (CFs) and micronutrient products – was employed. Among the treatments, the combination of CFs, Tracs Sure, and Akre Shield significantly improved FCV tobacco cured leaf yield (13–14%) and numerically improved nutrient uptake and nutrient use efficiency. Leaf quality parameters under both NLS and SLS conditions were within the acceptable limits. This is the first study to evaluate the suitability of customized fertilizers (CFs) for FCV tobacco in the NLS and SLS regions. All fertilizer treatments supplied the region-specific recommended nutrient doses, but CFs supplied the nutrients in one standardized formula, reducing the chances of over- or under-application associated with field use of individual straight fertilizers. Results showed that the CF formulations developed were suitable for both regions, thus recommending their adoption by the FCV tobacco farming community.

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Introduction

Tobacco (*Nicotiana tabacum* L.) is an important commercial crop in India, providing livelihood security to 45.7 million people in the country. India is the second-largest tobacco producer (770 million kg) worldwide and one of the top producers and exporters of tobacco from 2024 to 2025; during this period, India earned approximately US$ 1.98 billion from tobacco exportation (Tobacco Board et al. 2026). Among the types of tobacco exported from India, namely burley, bidi, cigar, cheroot and chewing tobaccos, Flue-cured Virginia (FCV) tobacco is considered a high-quality export product because it exhibits a bright color, exudes a pleasant odor, burns well, and cures evenly. However, the occurrence of these quality traits depends on the application of an appropriate amount of nutrients because even minor fluctuations in nutrient supply can affect the chemical composition, curing, and quality of FCV tobacco. In contrast, excessive N worsens quality and efficiency (Krishna Reddy et al. 2017).

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Nitrogen (N), phosphorus (P), and potassium (K) are the most important nutrients for FCV tobacco production. However, the northern light soils (NLS) and southern light soils (SLS), both classified as light-textured Alfisols, where FCV tobacco is grown in Andhra Pradesh, India, have low-to-medium organic carbon (C) content (0.25–0.40%) and are vulnerable to nutrient leaching (Rao and Reddy 1996; Prasad et al. 2021). Prasad et al. 2021 reported in a tobacco soil fertility assessment study that 73% NLS ranged from very low to low in zinc and 23% of NLS were reported as low for copper; and very low to low in zinc in SLS (Prasad et al. 2016) . Field experiments involving FCV tobacco in India have consistently shown that nutrient use efficiency indices, namely agronomic efficiency (AE), recovery efficiency (RE), and partial factor productivity (PFP), exhibit significant sensitivity to N×K interactions, timing, and sources. When Alfisols were irrigated to optimize N and K, they exhibited higher AE, RE, and PFP values than farmer or blanket rates (Krishna Reddy et al. 2017). Hence, fertilizer management is important for maintaining FCV tobacco productivity and competitiveness in the export market.

Most farmers apply striaght fertilizers (SFs), namely, diammonium phosphate (DAP) as P and N sources, ammonium sulfate and urea as N sources, sulfate of potash (SOP) as a K source, and ammonium sulfate and urea as N sources, to FCV tobacco. However, during the COVID–19 pandemic, disruptions in fertilizer supply chains led to reduced availability and increased prices of imported SOP (Emmanuel et al. 2021; Poorna Bindu et al. 2025). Owing to the high cost and unavailability of K fertilizers during unforeseen situations, small and marginal farmers typically do not apply K fertilizers (Tobacco Board, 2026) leading to imbalanced fertilization and suboptimal crop performance (Reddy et al. 2021). In the case of SFs which are typically used by farmers, DAP, SOP, and ammonium sulfate can lead to uneven distribution in the field because of variations in their physical forms. CFs are single fertilizers with all NPK, granular in physical form and contain a balanced proportion of nutrients, therefore promote uniform application of NPK in the root zone, and promoting nutrient absorption (Havlin et al. 2014). K fertilizer accounts for approximately 58% of the fertilizer cost in FCV tobacco production and therefore acts as a major economic constraint (Reddy et al. 2021). A study by the Tobacco Board (2023) observed that the cost of SOP has increased year-over-year and the tobacco growers are reducing or avoiding SOP application owing to its exorbitant price.

Liebig's Law of the Minimum states that a nutrient at deficient levels limits crop growth potential (Fageria et al. 2011). In FCV tobacco production, farmers typically use SFs and consequently tend to over-apply phosphorus resulting in a high phosphorus status of tobacco soils (Prasad et al. 2021) from diammonium phosphate and under-apply K because of the high cost of SOP. K thus can become the limiting nutrient, limiting crop growth and nutrient use efficiency when other nutrients are provided in adequate amounts in FCV tobacco soils. Hence the application of balanced nutrients (NPK) in single-form customized fertilizers (CFs) ensures that no essential nutrient limits the yield potential of crops. CFs are crop- and site-specific nutrient formulations based on soil test data and crop nutrient requirements to ensure balanced nutrition and high nutrient use efficiency (Government of India 1985; Rakshit et al. 2012). Appropriate amounts of CFs should be applied to crops at the proper time and place by considering soil properties, crop nutrient needs, and agroclimatic conditions. The application of CFs may help in improving crop yield and soil health, as CFs reduce soil fertility decline (Choudhary et al. 2020) and soil nutrient depletion (Susan John and Anju 2023).

Mudalagiriyappa et al. (2015) reported that CFs enhanced nutrient absorption, particularly that of N and K, by ensuring nutrient accessibility during essential growth phases. Similarly, Pramanick et al. (2024) demonstrated that site-specific nutrient management, which is a conceptual equivalent of CFs, resulted in improved yield and nutrient use efficiency.

Several food, cereal and horticultural crops have been evaluated with CF formulations, where they have generally increased crop productivity, nutrient uptake or nutrient-use efficiency compared to conventional fertilizer practices. For example, positive responses have been reported in rice and wheat (Dwivedi et al. 2014; Singh et al. 2019), and in vegetable and tuber crops (Singh et al. 2019; Anju et al. 2020; Vidyashree and Arthanari 2021). These investigations have demonstrated the general value of

adapting the composition of the fertilizer to the nutrient requirements of the crop and to soil conditions. However, their results cannot be directly extrapolated to FCV tobacco as tobacco is grown for cured leaves rather than grain, fruit or tubers, and its commercial value is based not only on yield but also on leaf chemistry.

N and K management is particularly important in FCV tobacco, as insufficient supply of these nutrients limits leaf growth, while excessive or unbalanced nutrient application negatively impacts maturity and cured-leaf quality. Hence, field evaluation of the effects of CFs formulations on yield, nutrient uptake, nutrient-use efficiency, leaf quality and post-harvest soil fertility is needed for FCV tobacco. To our knowledge, such formulations have not been previously evaluated in FCV tobacco grown under the contrasting irrigated NLS and rainfed SLS. The present study was thus undertaken to fill this crop- and region-specific research gap with the aim of:

(1) Evaluating the performance of CFs formulations on yield, nutrient uptake, nutrient use efficiency and quality of FCV tobacco in NLS (irrigated) and SLS (rainfed) in Andhra Pradesh.
(2) Evaluating the performance of CFs formulations along with micronutrient products on yield, nutrient uptake, nutrient use efficiency and quality of FCV tobacco in NLS (irrigated) and SLS (rainfed) in Andhra Pradesh.

Materials and methods

Experimental site and soil characteristics

Field experiments were conducted from 2022 to 2024 at two sites in Andhra Pradesh, India, representing major FCV tobacco–growing regions: The Indian Council of Agricultural Research–National Institute for Research on Commercial Agriculture (ICAR–NIRCA) Regional Stations at Jeelugumilli Research Farm (17°21′ N, 81°13′ E) and Kandukur Research Farm (15°21′ N, 79°90′ E). The soil types at Jeelugumilli and Kandukur Research Farms were NLS and SLS, respectively. The FCV tobacco plants at Jeelugumilli Research Farm were cultivated under irrigated conditions, whereas those at Kandukur Research Farm were cultivated under rainfed conditions.

At each site, the field experiments employed a randomized complete block design with nine treatments separately for NLS and SLS with three replicates. At both sites, 60-day-old FCV tobacco seedlings from nursery of respective farms were transplanted during the second week of October each year, and recommended good agricultural practices were followed. FCV tobacco was grown following standard agronomic practices as recommended by ICAR–NIRCA separately under irrigated NLS and SLS.

In the irrigated NLS, deep plowing and disking were done with a tractor at the beginning of the southwest monsoon. Transplanting was done in mid-October at a distance of 100 × 60 cm. Seedlings were transplanted in furrows and then ridged after about 40 days of transplanting. Fertilizers were added by dollop placement near the plant according to the treatment schedule. The recommended dose of fertilizer was 115:36:120kg $N:P_2O_5:K_2O$ ha^{-1}. A total of 8 to 10 irrigations were given as per crop requirement. Two intercultivations were performed up to 40 days after transplanting and then ridging was done. Topping was done at flower bud initiation leaving 24 leaves per plant. Sucker control was carried out by the use of 4% decanol fatty alcohol and hand desuckering when necessary. Mature leaves were harvested by sequential priming, cured in conventional flue-curing barns, and classified by plant position.

Deep plowing was carried out in July–September before transplanting in the rainfed SLS. Transplanting was done in mid-October with a spacing of 70 × 50 cm. Flat-bed planting was done followed by earthing-up/ridging and fertilizers were applied in plant row-plow furrows according to the treatment schedule. The recommended dose of fertilizer was 60:36:60 kg $N:P_2O_5:K_2O$ ha^{-1}. The crop was rainfed and one life saving irrigation was given at 40–45 days after planting because of a dry spell as per recommendation. Intercultivation was done twice before 40 days after transplanting.

Plants were topped at the bud stage and suckers were controlled with 4% Decanol and then manually desuckered. Mature leaves were harvested via sequential priming and then flue-cured and graded at the farm to commercial quality standards.

For NLS, two CF grades were specifically developed for the NLS region and one grade for FCV tobacco in the SLS region and evaluated in collaboration with Fertis India Pvt. Ltd., Hyderabad, Telangana, India. The CFs basal grade of NLS consisted of N, P_2O_5, K_2O, sulfur (S), and calcium (Ca) at a ratio of 12:18:14:4.5:2.5. In contrast, the CFs top-dress grade consisted of N:P_2O_5:K_2O:S at a ratio of 17:0:17:9.5. Altogether, these grades provided 117.5, 36, 121.5, 61.3, and 5 kg ha^{-1} of N, P_2O_5, K_2O, S, and Ca, respectively to the CF treatments, equivalent to 100% of the recommended dose of fertilizers. At NLS, recommended doses of N, phosphorus pentoxide (P_2O_5), and potassium oxide (K_2O) fertilizers for NLS were applied at 117.5 kg ha^{-1}, 36 kg ha^{-1}, and 121.5 kg ha^{-1}, respectively for SF treatment through straight fertilizers in three splits.

At SLS, the CFs basal grade, with an N:P_2O_5:K_2O:S:Ca ratio of 16:10:18:6:1.5, supplied 60, 37.5, 67.5, 22.5, and 5.6 kg ha^{-1} of N, P_2O_5, K_2O, S, and Ca, respectively for CF treatments. The recommended doses of N, phosphorus pentoxide (P_2O_5), and potassium oxide (K_2O) were applied at 60, 37.5, 67.5, 22.5, and 5.6 kg ha^{-1} of N, P_2O_5, K_2O, S, and Ca, respectively for SF treatment through SFs at basal.

Secondary and micronutrient products such as Tracs Sure (zinc, magnesium, copper, iron, boron, molybdenum) and Akre Shield (containing phenols 3%) were evaluated in combination with the CFs. Both the products were manufactured by Fertis India Pvt. Ltd., Hyderabad, India.

The treatments comprised combinations of split and basal applications of CFs, with or without Tracs Sure (18 kg ha^{-1}), Akre Shield (1 ml L^{-1} at 25 and 45 days after transplanting), and secondary/micronutrient mixtures, compared with the recommended NPK through SFs and an absolute control. The control and treatment set-ups in the field experiments conducted at both sites are shown in Table 1. Hereafter, the treatments will be referred to by their respective abbreviations.

Prior to planting, surface soil samples (0–15 cm) were collected from each plot and analyzed for the following key soil properties: pH, electrical conductivity (EC), organic C, and available K. The soil samples collected from NLS exhibited a sandy loam texture (pH: 6.5; EC: 0.24 dS m^{-1}; organic C: 2.53 g kg^{-1}; available P: 65 kg ha^{-1}; available K: 350 kg ha^{-1}), whereas those from SLS exhibited a loamy texture (pH: 7.5; EC: 0.24 dS m^{-1}; organic C: 3.45 g kg^{-1}; available P: 28 kg ha^{-1}; available K: 295 kg ha^{-1}).

Table 1. Control and treatment setups in field experiments conducted at Jeelugumilli Research Farm and Kandukur Research Farm, representing tobacco-growing regions with northern light soil (NLS) and southern light soils (SLS), respectively, in Andhra Pradesh, India.

		Jeelugumilli Research Farm (NLS)		Kandukur Research Farm (SLS)
Treatments	CF1	Customized fertilizer (basal) & 2 top dressings	CF1	Customized fertilizer (basal)
	CF2	Customized fertilizer (basal) & 2 top dressings + micronutrient fertilizers	CF2	Customized fertilizer (basal) + micronutrient fertilizers
	CF3	Customized fertilizer (basal) & 2 top dressings + Tracs Sure	CF3	Customized fertilizer (basal) + Tracs Sure
	CF4	Customized fertilizer (basal) & 2 top dressings + Tracs Sure + Akre Shield	CF4	Customized fertilizer (basal) + Tracs Sure + Akre Shield
	CF5	Customized fertilizer (basal) & 3 top dressings	CF5	Customized fertilizer (basal) & 1 top dressing
	CF6	Customized fertilizer (basal) & 3 top dressings + Tracs Sure	CF6	Customized fertilizer (basal) & 1 top dressing + Tracs Sure
	CF7	Customized fertilizer (basal) & 3 top dressings + Tracs Sure + Akre Sheild	CF7	Customized fertilizer (basal) & 1 top dressing+ Tracs Sure + Akre Shield
	SF	Straight fertilizers	SF	Straight fertilizers
	UC	Unfertilized cropped control	UC	Unfertilized cropped control

Tracs Sure (concentration: 18 kg ha^{-1}); Akre Shield (concentration: 1 ml L^{-1} applied at 25 and 45 days after transplanting).

Yield and quality parameters

Green leaf yield (GLY)

Mature leaves were harvested by priming (i.e., two to three leaves were picked at intervals of 7–8 days). Fresh leaf weight was recorded and expressed as kg ha^{-1}.

Cured leaf yield (CLY)

The harvested leaves were cured in conventional flue-curing barns following the standard FCV tobacco curing schedule. The curing process was done in four stages in a consecutive order: i) yellowing (32–38°C, 85–90% relative humidity), ii) color fixation (38–48°C), iii) leaf drying (48–60°C) and iv) midrib drying (60–72°C). The leaves were then conditioned, graded and weighed to determine cured leaf yield and expressed in terms of kg ha^{-1}.

Bright leaf yield (BLY)

Grading was based on the size, color, body, maturity, texture, and blemish percentage of the cured leaves. The grade index (GI) of the cured-leaf samples from the NLS was computed by assigning relative weights to grades and expressing them as a percentage. In contrast, the quality of the samples from the SLS region was expressed as BLY, representing the relative weights of the two brightest grades. Bright leaf grades are cured leaves with a bright lemon to orange color, with good leaf body, maturity, texture and blemish-free. Bright grades are graded according to the grading standards and are considered the highest value commercial grades because of their superior smoking quality and market acceptability.

Estimation of nicotine, reducing sugars, and chlorides

In NLS, representative sample leaves from X position leaves (two and three primings) and L position (four, five and six primings) and for SLS, bright leaf and composite leaf (all primings) were collected as per the recommendation of ICAR-NIRCA. The midrib was removed from the leaf samples, and the stripped lamina portions were dried in an air oven at 60°C. Subsequently, the oven-dried samples were powdered and then passed through a 60-mesh sieve (0.2 mm) for quality analysis. Afterward, 0.25 g of the leaf lamina powder was placed in a 150-mL conical flask. Then, 2 mL of a carbon suspension (Qualigens, Hyderabad, India) and 48 mL of an extracting solution (Qualigens, Hyderabad, India) were added to the flask. The resulting solution was shaken well for 15 min at 170 rpm. The solution was filtered and placed in cuvettes.

Nicotine was determined by direct colorimetry using an Auto Analyzer (AAS, Bran+Luebbe, Germany) according to the method described by Harvey et al. (1969). Nicotine was treated with the reagent cyanogen bromide (CNBr) in aniline buffer to yield a yellow colored complex. Absorbance was measured at 460 nm and the nicotine concentration was calculated from a standard calibration curve.

Reducing sugars were measured by the inverse colorimetric method with potassium ferricyanide. Reducing sugars in alkaline medium reduced the yellow potassium ferricyanide to colorless potassium ferrocyanide. The decrease in color intensity was measured at 420 nm and the concentration of reducing sugar was calculated using the respective standard calibration curve.

The chloride content was determined by direct colorimetry with mercuric thiocyanate-ferric nitrate reagent. Chloride ions displaced mercuric thiocyanate and the liberated thiocyanate reacted with ferric nitrate to give a blood-red complex of ferric thiocyanate. Absorbance was read at 480 nm and chloride concentrations were calculated from a standard calibration curve.

Calibration standards of nicotine, reducing sugars and chlorides were prepared before analysis. All measurements were done on a stable baseline by an Auto Analyzer. Nicotine, reducing sugars and chlorides were expressed in percentage concentration on dry weight basis according to standard analytical methods described by Harvey et al. (1969) and Hanumantha Rao et al. (1980).

Soil analysis

The soil pH and EC of a 1:2.5 soil–water suspension were determined using a digital glass electrode pH meter (Systronics, Hyderabad, India) (Jackson 1973) and a digital conductivity meter (Systronics, Hyderabad, India), respectively. EC was expressed as dS m^{-1}. Organic C was determined using the Walkley–Black wet oxidation method (Walkley and Black 1934). Available P was extracted with the Bray reagent (Thermo Fisher Scientific, Hyderabad, India) for acidic soils and Olsen's reagent (Thermo Fisher Scientific.) for neutral-to-alkaline soils. Subsequently, available P was estimated using a UV-VIS spectrophotometer (Systronics, Hyderabad, India) (Jackson 1973). Available K was extracted using neutral 1 N ammonium acetate (Thermo Fisher Scientific) (Jackson 1973) and measured using a flame photometer.

Plant analysis

The N, P, and K contents of FCV tobacco roots, stems, and leaves were estimated using the standard methods established by Singh et al. (1999). Plant samples for N determination were digested in sulfuric acid at a temperature between 360 and 410°C, and potassium sulfate was used for raising the boiling temperature of sulfuric acid. After completion of digestion, samples were diluted and estimated using Auto Analyzer Plant samples for P and K determination were digested using the wet oxidation method using a diacid mixture. Samples were initially pre-digested with nitric acid overnight. Subsequently, diacid digestion was performed with a nitric acid (HNO_3) and perchloric acid ($HClO_4$) mixture (10:4) until a clear solution was obtained. After cooling, digest was diluted with water. Phosphorus was estimated using the vanado molybdo phosphoric yellow color method using UV-VIS spectrophotometer (Systronics 2202 Hyderabad, India). K was estimated using a flame photometer (Systronics 128 Hyderabad, India).

Estimation of nutrient uptake

Composite-cured leaf samples (proportions from all the picked leaves) and plant samples (stems and roots) were collected at the final harvest. Dry matter was recorded separately for the roots, stems, and cured leaves. Nutrient uptake (N, P, K) was computed by multiplying the nutrient concentration in each plant part by its respective dry weight and then summing the values into an estimate of total nutrient uptake (kg ha^{-1}).

Nutrient use efficiency indices

Nutrient use efficiency was calculated using the standard formulas.

Partial factor productivity (PFP) for (kg kg^{-1}): The partial factor productivity from applied NPK is the ratio of cured leaf yield in treated plot to amount NPK applied.

$PFP = Y/A_{NPK}$

Agronomic Efficiency (AE): It is the increase in crop yield per unit of NPK applied.

(i.e., ratio of the increase in yield to the amount of NPK applied) and expressed as kg^{-1}.

$AE = (Y - Y_0)/A_{NPK} = \Delta Y/A_{NPK}$

Apparent Recovery Efficiency of N (RE_N): It refers to the increase in N uptake by plant per unit of N applied. The RE is generally expressed in percentage terms (%).

$RE_N = (NU - NU_0)/A_N) \times 100 = (\Delta NU/A_N) \times 100$

Apparent Recovery Efficiency of K (RE_K): It refers to the increase in K uptake by plant per unit of K applied. The RE is generally expressed in percentage terms (%).

$RE_K = ((KU - KU_0)/A_K) \times 100 = (\Delta KU/A_K) \times 100$

Statistical analysis

The data collected from the field experiments conducted at both sites were subjected to analysis of variance, according to the procedures outlined by Panse and Sukhatme (1985). The difference between treatments was analyzed by F-test at $p \leq .05$. The means of treatment were separated by Duncan's Multiple Range Test at 5% probability level (Duncan 1955) when the effect of the treatment was significant. Means followed by the same letter were not statistically significant while means with different letters were significantly different at $p \leq .05$.

Results and discussion

FCV tobacco yield

The application of CFs and micronutrient supplements significantly affected the GLY, CLY, and GI of the FCV tobacco leaves from the NLS region and GLY, CLY, BLY of the FCV tobacco leaves from the SLS region. In the NLS region, the FCV tobacco treated with customized fertilizers at basal and three top dressings together with tracs sure and akre shield (CF7 NLS) exhibited the highest green leaf yield (19,880 kg ha^{-1}), cured leaf yield (2,781 kg ha^{-1}), and grade index (1,876 kg ha^{-1}). The CF7 treatment was significantly superior to straight fertilizers SF by 13%, 13.3% and 15.9%, respectively [$p = .05$] (Table 2). Similarly in the SLS (rainfed) region, the same treatment combination CF7-SLS produced the highest green leaf yield (15,643 kg ha^{-1}), cured leaf yield (2,503 kg ha^{-1}), and bright leaf yield (1,694) compared with straight fertilizers by 11%, 13.7% and 12.9%, respectively [$p = .05$] (Table 3). Increased FCV tobacco yields indicate the advantage of a balanced nutrient supply through the application of CFs and micronutrients at split doses at the right time under different soil and moisture conditions

Farmers generally apply N, P, and K fertilizers in different physical forms such as granular Diammonium phosphate, powdered SOP, and crystalline ammonium sulfate and mix them before application. This practice can lead to uneven distribution of nutrients in the field, resulting in imbalanced nutrient supply to the crop. In contrast, customized fertilizers, formulated in a uniform granular form, ensure consistent and balanced delivery of all essential nutrients to each plant.

The increment of cured leaf yield with customized fertilizers might be attributed to efficient absorption of NPK and other nutrients from tracssure and akre shield, which increased the production of the dry matter from source to sink. This may be due to continuous and gradual supply of all the nutrients from CF to the plant to maintain greenness of leaves for a longer period and thereby

Table 2. Effect of customized fertilizers, along with micronutrient products, on the productivity (kg ha^{-1}) of flue-cured Virginia tobacco grown in the northern light soil region of Andhra Pradesh, India (pooled).

Treatments	Green leaf yield	Cured leaf yield	Grade Index
CF1	17,069^{cd}	2437^{b}	1647cd
CF2	18,106^{bc}	2577^{ab}	1673^{cd}
CF3	17,849^{bc}	2455^{b}	1729^{bc}
CF4	18,058^{bc}	2643^{ab}	1770^{abc}
CF5	19,142^{ab}	2640^{ab}	1882^{a}
CF6	18,932^{ab}	2645^{ab}	1833^{ab}
CF7	19,880^{a}	2781^{a}	1876^{a}
SF	17,459^{bcd}	2454^{b}	1618^{d}
UC	10,131^{e}	1067^{c}	950^{e}
± SEM	523	69	58
CD ($p = .05$)	1515	201	168
Seasons			
Year 1	17,322^{a}	2387^{a}	1645^{a}
Year 2	17,484^{a}	2434^{a}	1684^{a}
± SEM	261	35	29
CD ($p = .05$)	757	100	84

Table 3. Effect of customized fertilizers, along micronutrient products, on the productivity (kg ha^{-1}) of flue-cured Virginia tobacco grown in the southern light soil region of Andhra Pradesh, India (pooled).

Treatments	Green leaf yield	Cured leaf yield	Bright leaf yield
CF1	14,464[a]	2278[a]	1535[a]
CF2	14,998[a]	2367[a]	1574[a]
CF3	14,053[a]	2427[a]	1573[a]
CF4	14,763[a]	2402[a]	1593[a]
CF5	14,739[a]	2447[a]	1571[a]
CF6	14,853[a]	2378[a]	1520[a]
CF7	15,643[a]	2503[a]	1694[a]
SF	14,160[b]	2201[b]	1500[b]
UC	5798	958[a]	700
± SEM	586	98	66
CD ($p = .05$)	1696	284	192
Seasons			
Year 1	12,959[b]	2132[b]	1387[b]
Year 2	14,478[a]	2304[a]	1559[a]
± SEM	293	49	33
CD ($p = .05$)	848	142	96

increased the photosynthetic rate, disease resistance and cell activity. The magnitude of yield improvement was higher under NLS (irrigated) than SLS (rainfed), which was indicative of the positive effect of adequate soil moisture on nutrient acquisition and biomass production. However, in both environments, CFs were always better than straight fertilizers, showing that the response was not specific to any system of production. This consistency shows that the customized formulations are suitable for irrigated and rainfed FCV tobacco cultivation when applied as per fertilizer recommendations for the respective regions.

Similar enhancements in CF-treated rice and wheat have been reported by Dwivedi et al. (2014) and Singh et al. (2019). Majumdar and Prakash (2018) demonstrated that CF application improved the yield of paddy, wheat, onions, and pomegranates. In elephant foot yam–coconut intercropping systems, Anju et al. (2020) applied CFs at a rate of 625 kg ha^{-1} and observed a significant improvement in tuber yield (up to 67.5 t ha^{-1}) compared with that achieved with the application of straight fertilizers (47.3 t ha^{-1}) and employment of other agricultural practices (51.6 t ha^{-1}). Kamble and Kathmale (2015) recorded the highest fertilizer use efficiency and bulb yield (22.34 t ha^{-1}) of onion after applying the 100% recommended dose of NPK in the form of a CF, which was distributed in three equal doses. Kaleeswari (2013) applied 100% RDF in the form of CFs to paddy fields and observed a 22.2% increase in yield compared with that achieved with straight fertilizers. The positive response of FCV tobacco to the application of CFs is consistent with these previous findings that the balanced and timely application of nutrients is crucial for yield improvement and customized fertilizers are suitable for both NLS and SLS.

Nutrient uptake

The CF treatments significantly improved the total N and K uptake by FCV tobacco in both the NLS and SLS regions. In the NLS (irrigated) region, the CF7-treated samples exhibited the maximum N uptake (113.08 kg ha^{-1}) and K uptake (124.82 kg ha^{-1}), which were significantly higher [$p = .05$] than those of the SF-treated samples (Table 4). Compared with the straight fertilizer treatment, N uptake increased by 3.7%, whereas K uptake increased by 16.4%. In the SLS (rainfed) region, the CFs combined with tracs sure and akre shield (CF7)-treated samples exhibited the maximum N uptake (68.62 kg ha^{-1}) and K uptake (124.82 kg ha^{-1}), which were significantly higher [$p = .05$] than those of the SF-treated samples with N uptake (57.22 kg ha^{-1} and 106.1 kg ha^{-1} (Table 5). Compared with the SF treatment, N uptake increased by 19.9%, whereas K uptake increased by 16.7%. The benefit of CFs over SFs was consistent across both locations suggesting that the response was independent of the

Table 4. Effect of customized fertilizers, along with micronutrient products, on the total nutrient uptake (kg ha^{-1}) of flue-cured Virginia tobacco grown in the northern light soil region of Andhra Pradesh, India.

Treatments	N Uptake	K Uptake
CF1	106.24	111.87
CF2	99.29	108.15
CF3	104.74	117.81
CF4	102.55	111.19
CF5	108.02	112.69
CF6	109.80	119.93
CF7	113.08	124.82
SF	109.08	107.21
UC	42	46
± SEM	5.71	5.80
CD ($p = .05$)	17.12	17.38

Table 5. Effect of customized fertilizers, along with micronutrient products, on the total nutrient uptake (kg ha^{-1}) of flue-cured Virginia tobacco grown in the southern light soil region of Andhra Pradesh, India.

Treatments	N Uptake	K Uptake
CF1	55.49	96.8
CF2	61.32	106.1
CF3	62.49	99.9
CF4	66.65	105.4
CF5	63.58	115.0
CF6	65.74	114.0
CF7	68.62	123.8
SF	57.22	106.1
UC	28.13	52.1
± SEM	4.61	6.68
CD ($p = .05$)	13.40	19.51

production environment. The increased cured leaf yield in the same treatments was closely associated with the better nutrient uptake because of the CFs. Biomass production was higher in the customized fertilizer treatments, and the nutrient uptake being the product of nutrient concentration and plant dry matter, it directly contributed to greater accumulation of N and K in plant tissues. All treatments in the present study received the same amounts of N, P_2O_5 and K_2O within each location; thus any differences in nutrient uptake were attributed to fertilizer formulation and associated treatment combinations and not to differences in the rates of nutrients applied. Vidyashree and Arthanari (2021) reported that at 150% dose, CFs improved N (117 kg ha^{-1}), P (21 kg ha^{-1}), K (150 kg ha^{-1}), S (96 kg ha^{-1}), and Zn (230 g ha^{-1}) uptake by wheat. The higher N and K uptake of tobacco grown in both the regions was observed with customized fertilizer (CF) application compared to those of straight fertilizers. The reasons could be attributed to nutrient balance, uniformity, and synchronization with crop growth and nutrient demand. In case of SFs, which is typical farmer practice, DAP, SOP, and ammonium sulfate can lead to uneven distribution in the field because of their physical forms' variation. CFs are granular in the physical form and contain a balanced proportion of nutrients, therefore promote uniform application of N, P, and K in the root zone, thereby promoting nutrient absorption (Havlin et al. 2014). CFs minimize nutrient deficiency effects, which are common in imbalanced fertilization and improve membrane transport, enzyme activation, and photosynthesis, ultimately enhancing nutrient uptake efficiency (Fageria 2001; Marschner 2012). Improved nutrient use efficiency parameters, including AE and RE, under CF treatments further indicate reduced nutrient losses and enhanced nutrient acquisition by plants (Baligar et al. 2001). Thus, the uniform nutrient distribution, balanced supply, reduced losses, and synchronization with crop demand make CFs more effective than SFs in enhancing N and K uptake of FCV tobacco growing regions.

Nutrient use efficiency

AE, and PFP, and the REs of N and K (RE_N and RE_K) considerably differed among the treatments. The FCV tobacco samples treated with CFs consistently had higher NUE than those treated with straight fertilizers. The highest NUE was achieved by applying the CF7 treatment. Nonetheless, the AE, PFP, RE_N, and RE_K of the CF7-treated FCV tobacco samples were only slightly higher than those of the SF-treated samples. This suggests that combining CFs with Tracs Sure and Akre Shield promotes improved NUE and yield, offering a potentially more efficient fertilizer strategy for tobacco farmers (Figure 1). Targeted nutrient delivery through CFs enhances NUE by minimizing losses from leaching, volatilization, and fixation, thereby ensuring greater conversion of applied nutrients into biomass and yield.

Quality parameters

In the NLS region, the nicotine content of X-position leaves was 1.20–1.56%, whereas that of L-position leaves was 2.06–2.50%. The treatments wherein CFs were combined with Tracs Sure + Akre Shield produced balanced nicotine-to-reducing sugar ratios (1.47–13.25%). The chloride content of the leaves (1.13%) was below the critical threshold of 1.5% (Table 6). Similarly, in the SLS region, the FCV tobacco samples treated with a combination of CF, Tracs Sure, and Akre Shield produced leaves with nicotine and reducing sugar levels of 2.11% and 9.28%, respectively. Their chloride levels were minimal (0.14–0.24%) (Table 7). The values of all leaf quality parameters were within acceptable limits, indicating that CFs are as safe as straight fertilizers in maintaining the leaf quality of FCV tobacco in

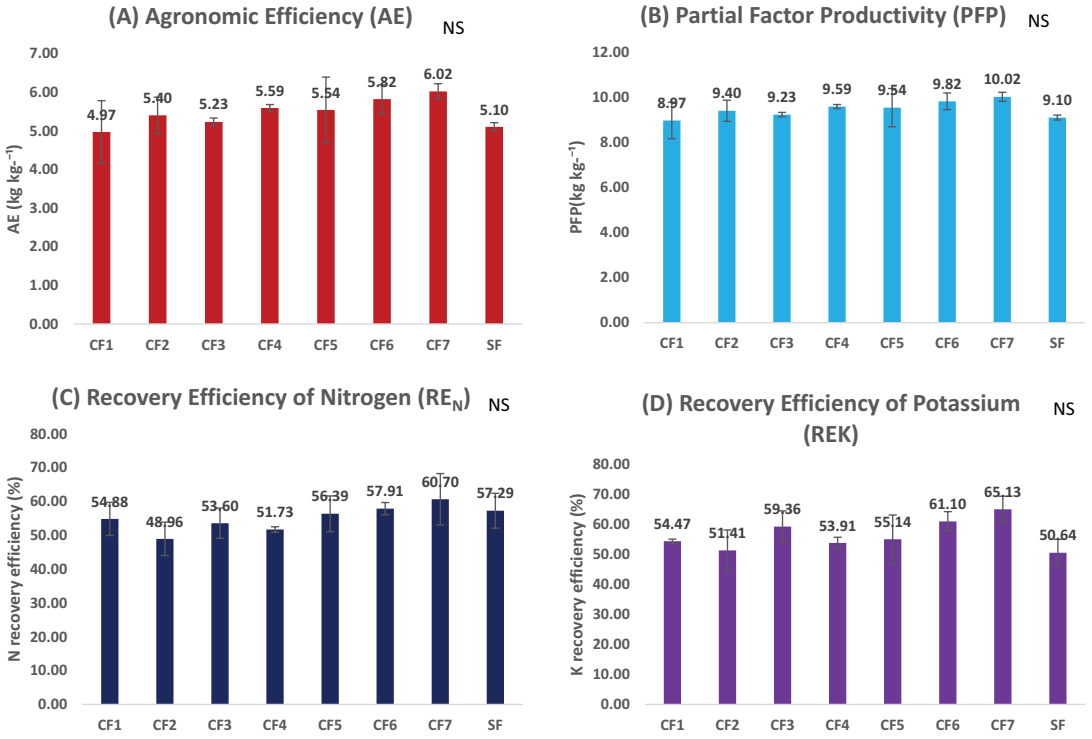

Figure 1. Effect of customized fertilizers, along with micronutrient products, on the nutrient use efficiency of flue-cured tobacco grown in the northern light soil region of Andhra Pradesh, India: (A) agronomic efficiency (AE), (B) partial factor productivity (PFP), (C) recovery efficiency of nitrogen (RE_n), and (D) recovery efficiency of potassium (RE_k). Error bars represent the standard error of the mean. NS indicates a nonsignificant difference among treatments at $p > .05$. CF1–CF7 represent customized-fertilizer treatments, and SF represents the straight-fertilizer treatment. Figure 1A. Agronomic efficiency; Figure 1B. Partial factor productivity; Figure 1C. Recovery efficiency of nitrogen (REN), Figure 1D. Recovery efficiency of potassium (REK).

Table 6. Effect of customized fertilizers on the quality parameters (%) of flue-cured Virginia tobacco grown in the northern light soils.

	Nicotine		Reducing Sugars		Chlorides	
Treatments	X Position	L Position	X Position	L Position	X Position	L Position
CF1	1.48	2.50	13.57	8.50	1.43	1.13
CF2	1.36	2.37	13.33	8.37	1.46	0.99
CF3	1.34	2.22	13.58	8.52	1.46	1.11
CF4	1.20	2.13	12.53	8.36	1.44	0.97
CF5	1.25	2.21	13.26	8.54	1.47	1.06
CF6	1.39	2.06	13.64	8.41	1.59	1.08
CF7	1.47	2.18	13.25	8.61	1.47	1.15
SF	1.56	2.28	13.34	8.71	1.41	1.13
UC	0.72	1.48	13.60	12.43	1.51	0.97
± SEM	0.07	0.15	0.48	0.29	0.06	0.11
CD($p = .05$)	0.22	0.44	1.45	0.86	0.18	0.33

Table 7. Effect of customized fertilizers on the quality parameters (%) of flue-cured Virginia tobacco grown in southern light soils.

	Nicotine		Reducing Sugars		Chlorides	
Treatments	Bright leaf	Composite leaf	Bright leaf	Composite leaf	Bright leaf	Composite leaf
CF1	1.95	1.54	9.55	10.52	0.19	0.32
CF2	1.68	1.43	9.79	10.69	0.20	0.31
CF3	1.69	1.44	9.47	9.81	0.17	0.32
CF4	1.88	1.73	9.07	9.08	0.21	0.34
CF5	1.74	1.60	8.33	9.90	0.20	0.33
CF6	1.95	1.55	9.09	9.87	0.16	0.27
CF7	2.11	1.62	9.28	9.58	0.14	0.24
SF	2.00	1.42	8.14	9.52	0.23	0.34
UC	1.69	1.39	8.02	8.89	0.40	0.61
± SEM	0.14	0.14	0.58	0.75	0.03	0.07
CD ($p = .05$)	0.30	0.29	1.20	1.55	0.06	0.15

both the NLS and SLS regions. This could be attributed to the absence of excessive nutrients in the soil as a result of the application of CFs, tracs sure, akre shield paving the way for normal nutrient profiles. These results are consistent with the findings of Anju et al. (2020), who reported that CF application improved tuber quality; specifically, starch (up to 16.2%), crude protein (16.7%), and ash contents increased, while anti-nutritional factors, such as calcium oxalate, were maintained at acceptable levels.

Post-harvest soil properties

In the NLS region, available N, P, K were higher in the plots applied with a combination of CF + Tracs Sure + Akre Shield than in the unfertilized cropped control (Table 8). In the SLS region, soil pH ranged from 6.40 to 7.90 and organic C content remained stable across the treatments (0.17–0.23%), indicating that none of the treatments had adverse effects on soil organic matter. Nutrient availability (N, P, and K) varied slightly among the treatments; however, the differences were not statistically significant (Table 9). In light textured soils, poor cation exchange capacity promotes nutrients to leaching losses, the balanced and synchronized nutrient supply from CFs improves nutrient retention, thereby increases the residual soil fertility. The integration of secondary and micronutrients (through Tracs Sure) and phenolic effects (Akre Shield) might have further stimulated rhizomicrobiome activity, and thereby nutrient transformations (Richardson et al. 2009). Similar findings have been reported by Ramasubramanian et al. (2025), where balanced and precision nutrient management practices improved soil nutrient status and microbial activity compared to SFs.

Overall, the CF treatments improved soil fertility compared with SFs and the unfertilized cropped control. The combination of CF, Tracs Sure, and Akre Shield resulted in the most balanced soil pH, organic C, and available nutrients in both regions. Improvements in nutrient pools confirmed the

Table 8. Effect of customized fertilizers, along with micronutrient products, on soil properties in the northern light soil region of Andhra Pradesh, India.

Treatments	Soil pH (1:2)	OC (%)	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
CF1	5.33	0.51	180	89	635
CF2	5.12	0.44	176	83	419
CF3	5.39	0.46	180	77	541
CF4	5.38	0.44	176	85	511
CF5	5.15	0.46	159	76	452
CF6	5.09	0.47	180	91	527
CF7	4.92	0.47	201	110	579
SF	5.18	0.51	167	98	607
UC	5.01	0.36	184	56	392
± SEM	0.12	0.03	17	5	28
CD ($p = .05$)	0.37	0.10	52	11	83

OC: organic carbon.

Table 9. Effect of customized fertilizers, along with micronutrient products, on soil properties in the southern light soil region of Andhra Pradesh, India.

Treatments	Soil pH (1:2)	OC (%)	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
CF1	7.87	0.21	71	52	376
CF2	7.07	0.17	71	61	356
CF3	6.40	0.23	88	76	374
CF4	7.17	0.21	79	57	384
CF5	7.00	0.21	79	61	378
CF6	7.23	0.22	71	60	339
CF7	7.50	0.22	80	61	371
SF	7.90	0.22	67	62	417
UC	7.50	0.22	54	55	285
± SEM	0.26	0.01	8	4	24
CD ($p = .05$)	NS	NS	NS	NS	NS

OC: organic carbon.
NS: Non Significant.

residual benefits of CF beyond the immediate yield responses. These findings are consistent with those of Fageria et al. (2011) and Choudhary et al. (2020), who emphasized that CFs help improve NUE and sustain soil fertility over time, especially in countries where blanket fertilizer recommendations for different crops have resulted in a poor nutrient supply, low NUE, and limited crop response, by ensuring appropriate fertilization (Majumdar and Prakash 2018).

Conclusion

Customized fertilizers proved suitable for both northern light soils and southern light soils. Further CFs, in combination with micronutrient products such as Tracs Sure and Akre Shield, enhanced the green leaf yield, cured leaf yield and bright leaf yield of FCV tobacco grown in the NLS (irrigated) and SLS (rainfed) regions significantly. N and K uptake, and NUE were numerically higher and at a par with straight fertilizers. Additionally, key leaf quality parameters, such as nicotine and reducing sugars, remained within acceptable limits. Furthermore, CFs doesn't affected soil fertility, making them a sustainable and efficient solution for applying balanced nutrients to FCV tobacco. The application of CFs, along with Tracs Sure and Akre Shield, will help the tobacco farming community in enhancing the yield of FCV tobacco at less expenses. Recommendations for the application of CFs at basal and three topdressings, along with Tracs Sure and Akre Shield for NLS and application of CFs at basal and one topdressing along with Tracs Sure and Akre Shield for SLS, were provided to the tobacco farming community for balanced nutrient application and enhanced yield of FCV tobacco grown under irrigated and rainfed conditions.

Abbreviations

Abbreviation	Definition
AE	Agronomic efficiency
BLY	Bright leaf yield
CD	Critical difference
CF	Customized fertilizer
CLY	Cured leaf yield
DAP	Diammonium phosphate
DMRT	Duncan's Multiple Range Test
EC	Electrical conductivity
FCV	Flue-cured Virginia
GI	Grade index
GLY	Green leaf yield
NLS	Northern Light Soils
NUE	Nutrient use efficiency
PFP	Partial factor productivity
RDF	Recommended dose of fertilizer
RE	Recovery efficiency
REK	Apparent recovery efficiency of potassium
REN	Apparent recovery efficiency of nitrogen
SEM	Standard error of the mean
SF	Straight fertilizer
SLS	Southern Light Soils
SOP	Sulfate of potash
UC	Unfertilized cropped control

Symbols and Chemical Notation

Symbol	Definition
C	Carbon
Ca	Calcium
K	Potassium
K_2O	Potassium oxide
N	Nitrogen
NPK	Nitrogen, phosphorus and potassium
P	Phosphorus
P_2O_5	Phosphorus pentoxide
S	Sulfur
Y	Cured leaf yield in the fertilized treatment
Y_0	Cured leaf yield in the unfertilized control
ΔY	Increase in cured leaf yield due to fertilizer application
A_{npk}	Amount of NPK applied
NU	Nitrogen uptake in the fertilized treatment
NU_0	Nitrogen uptake in the unfertilized control
ΔNU	Increase in nitrogen uptake due to N application
A_n	Amount of nitrogen applied
KU	Potassium uptake in the fertilized treatment
KU_0	Potassium uptake in the unfertilized control
ΔKU	Increase in potassium uptake due to K application
A_k	Amount of potassium applied

Units and Other Symbols

Symbol	Definition
%	Percent
°C	Degree Celsius
cm	Centimeter
dS m^{-1}	Decisiemens per meter
g	Gram
g kg^{-1}	Grams per kilogram

ha	Hectare
kg	Kilogram
kg ha^{-1}	Kilograms per hectare
kg^{-1}	Kilograms per kilogram
L	Liter
mL	Milliliter
mm	Millimeter
nm	Nanometer
rpm	Revolutions per minute
Δ	Change or difference
≤	Less than or equal to
±	Plus or minus

Statistical Term

Symbol/Term	Definition
ANOVA	Analysis of variance
DMRT	Duncan's Multiple Range Test
F-test	F-test for significance of treatment effects
P	Probability level
$p \leq .05$	Statistically significant at the 5% probability level
SEM	Standard error of the mean
CD	Critical difference at the specified probability level

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Author contributions

CRediT: **J. Poorna Bindu:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing; **M. Sheshu Madhav:** Project administration, Resources, Supervision, Validation; **M. Anuradha:** Conceptualization, Data curation, Investigation, Methodology, Writing – review & editing; **D. Damodar Reddy:** Conceptualization, Data curation, Funding acquisition, Methodology; **S. Kasturi Krishna:** Methodology, Visualization; **L.K. Prasad:** Formal analysis, Visualization; **C. Chandrasekhara Rao:** Formal analysis, Visualization; **Rajasekhara Rao Korada:** Project administration, Resources, Supervision, Writing – review & editing; **A. Jeyabal:** Funding acquisition.

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Data availability statement

Data supporting the findings of this study are available within the manuscript. Further information is available from the corresponding author on request and reasonable terms.

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