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# Sustainable Intensification of Rainfed Groundnut Farming: Assessing Mechanized *In situ* Rainwater Conservation Practices for Yield, Energy and Carbon Efficiency

Kishore Nalabolu[1], Ch. Ratna Raju[2], D. Srigiri[1]
V. Shobhan Naik[1], K. Arun Kumar[3], B.V. Mohana Rao[4]

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## ABSTRACT

**Background:** Groundnut (*Arachis hypogaea* L.) cultivation in semi-arid Andhra Pradesh is constrained by limited rainfall. Enhancing rainwater conservation is essential for improving productivity and resource efficiency. Mechanized in-situ rainwater conservation practices have emerged as interventions to address these challenges in recent years.

**Methods:** A field study evaluated eight mechanized *in situ* rainwater conservation techniques on groundnut yield, morphological characteristics, energy budgeting and carbon footprint indices during 2022-2023. Treatments included subsoiling, conservation furrows, broad bed and furrow, furrow diking and combinations. Subsoiling with furrow diking (T8), conservation furrow (T6) and broad bed and furrow (T7) were compared to a control (T1). The study assessed yield parameters, rainwater use efficiency, energy indices and carbon footprint using linear regression analysis.

**Result:** T8 significantly improved groundnut performance compared to the control, achieving the highest pod yield (361.2 kg $ha^{-1}$), haulm yield (2420 kg $ha^{-1}$) and RWUE (0.888 kg $ha^{-1}$ $mm^{-1}$), representing increases of 288%, 67% and 289% over T1, respectively. Growth parameters were superior under T6-T8. T8 recorded the highest energy output (47,717 MJ $ha^{-1}$) and net energy return (40,286 MJ $ha^{-1}$), while T6 exhibited the lowest specific energy (20.6 MJ $kg^{-1}$). Carbon intensity was reduced from 5.70 kg $CO_2$-eq $kg^{-1}$ in T1 to 2.32 kg $CO_2$ -eq $kg^{-1}$ in T8. Mechanized rainwater conservation enhanced yield, energy efficiency and carbon sustainability in semi-arid conditions.

**Key words:** Carbon footprint, Carbon intensity, Energy budgeting, Rainfed groundnut farming.

## INTRODUCTION

Rainfed agriculture constitutes 75-80% of global arable land, supporting millions of farmers with limited resources. In India, rainfed regions comprise 60% of the agricultural area, making rainwater management crucial for groundnut cultivation. Groundnut was selected for this study because of its importance as an oilseed crop in Ananthapuramu District andhra Pradesh, which accounts for 70% of the oilseed cultivation of state across 6-8 lakh hectares during the kharif season (Government of Andhra Pradesh, 2023). Groundnut (*Arachis hypogaea* L.) requires 500-700 mm rainfall due to its shallow roots and high evaporative demand, which is rare in drought-prone areas (Kumar *et al.*, 2020; Kishore *et al.,* 2022). The moisture sensitivity of this crop makes it ideal for assessing rainwater conservation techniques. Traditional rainfed farming faces challenges of unpredictable rainfall and soil moisture stress, which affect groundnut yields. In-situ water conservation techniques that capture and retain rainwater in the root zone can reduce the impacts of rainfall variability (Pathak *et al.,* 2013). This study examined various rainwater harvesting (RWH) and conservation tillage techniques. Practices such as contour bunding, broad bed furrows, subsoiling and conservation furrows improve moisture retention and ridge-furrow systems and surface mulching enhance soil water retention and infiltration efficiency (Bhattacharyya *et al.,* 2016; Hatfield and Walthall, 2015; Zheng *et al.,* 2022).

[1]Department of Farm Machinery and Power Engineering, College of Agricultural Engineering, Acharya N.G. Ranga Agricultural University, Madakasira-515 301, Andhra Pradesh, India.
[2]Department of Irrigation and Drainage Engineering, Dr. NTR College of Agricultural Engineering, Acharya N.G. Ranga Agricultural University, Bapatla-522 101, Andhra Pradesh, India.
[3]Department of Agronomy, Regional Agricultural Research Station, Acharya N.G. Ranga Agricultural University, Nandyal-518 503, Andhra Pradesh, India.
[4]Department of Soil and Water Conservation Engineering, College of Agricultural Engineering, Acharya N.G. Ranga Agricultural University, Madakasira-515 301, Andhra Pradesh, India.

**Corresponding Author:** Kishore Nalabolu, Department of Farm Machinery and Power Engineering, College of Agricultural Engineering, Acharya N.G. Ranga Agricultural University, Madakasira-515 301, Andhra Pradesh, India. Email: n.kishore@angrau.ac.in
ORCIDs: https://orcid.org/0009-0000-3889-4781, https://orcid.org/0000-0003-4645-2486, https://orcid.org/0000-0002-0562-2779

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Current policy priorities focus on enhancing agricultural yields while reducing the carbon footprint (CF). Mechanized

rainwater conservation requires increased energy inputs, creating a trade-off between the total emissions per hectare and emission intensity. In groundnut production, excluding haulm from functional units may inflate the CF (Zheng *et al.,* 2022; Notarnicola *et al.,* 2017). Most studies report emissions per hectare or pod yield, neglecting the haulms. Few studies have accounted for mechanization emissions from conservation tillage under semi-arid conditions. This study evaluated eight rainwater conservation treatments in rainfed groundnut to measure the emission efficiencies of pods, haulm and biomass. Including haulm analysis offers a comprehensive evaluation of groundnut production systems, identifying integrated mechanized practices as optimal strategies for dryland agriculture (Rockström *et al.,* 2010; Singh *et al.,* 2019). This study examined the effects of water harvesting, which is essential for improving productivity and resource efficiency and carbon emissions during rainfed groundnut cultivation. This study evaluated the effects of integrated rainwater harvesting techniques on groundnut morphology, performance and carbon footprint indices. The objectives were to (i) assess the effects of mechanized rainwater conservation on yield, (ii) investigate the impact of mechanization on morphology, (iii) evaluate energy budgeting and analyze carbon footprint parameters.

## MATERIALS AND METHODS

Field experiments were conducted during the 2022 and 2023 growing seasons at the College of Agricultural Engineering, Madakasira, a semi-arid region characterized by shallow red sandy loam soils, low fertility and annual rainfall ranging from 550 to 600 mm. Groundnut (*Arachis hypogaea* L.) is the predominant crop in this area, occupying over 60% of the agricultural land and is frequently intercropped with pigeonpea. Agriculture in this region faces challenges due to unpredictable rainfall, dry periods and inadequate moisture conservation practices, resulting in inconsistent crop yields. Eight different treatments were evaluated: T1 (control), T2 (subsoiling at 1 m intervals), T3 (conservation furrow), T4 (broad bed and furrow), T5 (furrow diking), T6 (T2 + T3), T7 (T2 + T4) and T8 (T2 + T5). The study employed a randomized block design with three replicates, with each plot measuring 10 × 10 m. Subsoiling (T2, T6, T7 and T8) was performed using a tractor-mounted chisel plough to a depth of 60 cm prior to primary tillage. Following a five-year fallow period, the land was prepared using mouldboard plough (30 cm), rotavator pulverization (25 cm), blade harrow leveling and a final pass with a rotavator. The groundnut variety K6, treated with carbendazim (2 g $kg^{-1}$ seed), was sown at a spacing of 30 × 10 cm. Treatments T1–T4 utilized a mini tractor-drawn planter, T5 and T8 employed a diker planter to create circular ditches and T6 and T7 used a broad-bed and furrow planter. Furrows and dikes (T4, T5, T7 and T8) were established at the time of sowing, whereas conservation furrows (T3 and T6) were formed 30 days later using an intercultivator with a spacing of 60 cm, depth of 10 cm and width of 22.5 cm.

Plant height is a fundamental agronomic trait that significantly influences crop growth and development. Although primarily governed by genetic determinants, it is also affected by the availability of soil moisture and nutrients. In the context of groundnut cultivation, root length is of paramount importance, as the pods develop along the subterranean root system, directly affecting the yield. Furthermore, haulm, which is a vital source of animal feed, was correlated with plant height. Mechanized *in-situ* conservation techniques have been shown to enhance soil moisture retention and augment crop yields under conditions of erratic rainfall (Feng *et al.,* 2024). This study assessed the variability in vegetation production within arid ecosystems, where growth is limited by rainfall. Rainwater use efficiency (RWUE) was calculated using Equation (1).

$$RWUE\ (\%) = \frac{Y}{R} \quad ....(1)$$

Where,

RWUE = Rainwater use efficiency.

Y = Yield of the crop (kg $ha^{-1}$).

R = Cumulative depth of rainfall from sowing to harvesting (mm).

Energy is integral to crop production and is embedded in both agricultural machinery and inputs. Data collected from various operations, spanning from land preparation to pod stripping, were converted into energy equivalents per unit area and were categorized by source. By employing standard conversion factors, the inputs and outputs were expressed in energy units to reveal the patterns of energy consumption. Under dryland conditions, the total energy, energy ratio, specific energy, energy productivity and net energy return were calculated using Equations (2-6) (Aytop, 2023).

Total output energy =

$$\text{Energy from groundnut kernels} + \text{Energy from groundnut haulm} \quad ....(2)$$

$$\text{Energy ratio}\ (\%) = \frac{O.E.}{I.E.} \quad ....(3)$$

$$\text{Specific energy}\ (MJ\ kg^{-1}) = \frac{I.E.}{Y} \quad ....(4)$$

$$\text{Energy productivity}\ (kg\ MJ^{-1}) = \frac{Y}{I.E} \quad ....(5)$$

$$\text{Net energy return} = O.E. - I.E. \quad ....(6)$$

Where,

O.E. = Output energy (MJ $ha^{-1}$).

I.E. = Input energy (MJ $ha^{-1}$).

Y = Crop yield (kg $ha^{-1}$).

The carbon footprint associated with groundnut production under various in-situ rainwater conservation methods was evaluated. This evaluation included emissions from field activities, such as mechanization, diesel and electricity consumption, as well as agricultural inputs such as fertilizers, pesticides and seeds, while excluding post-harvest processing and transportation (Pathak and Jain, 2011). The energy input per operation (MJ $ha^{-1}$) for tasks such as tillage, subsoiling, furrow diking, sowing, spraying, harvesting and pod stripping was documented and converted into carbon dioxide equivalents. This conversion employed emission factors of 2.68 kg $CO_2$-eq $L^{-1}$ for diesel (≈ 0.072 kg $CO_2$-eq $MJ^{-1}$) and 0.82 kg $CO_2$-eq kW $h^{-1}$ for electricity (≈0.23 kg $CO_2$-eq $MJ^{-1}$). The operational carbon footprint was calculated using Equation (7), as follows:

$$CF_{operations} = \Sigma (E_i + EF_i) \quad \ldots (7)$$

Where,

$E_i$ = Energy consumption of each operation (MJ $ha^{-1}$).

$EF_i$ = Corresponding emission factor (kg $CO_2$-eq $MJ^{-1}$).

Input related emissions were calculated using published coefficients of 6.3 kg $CO_2$-eq $kg^{-1}$ N, 1.5 kg $CO_2$-eq $kg^{-1}$ $P_2O_5$, 0.6 kg $CO_2$-eq $kg^{-1}$ $K_2O$, 5.1 kg $CO_2$-eq $kg^{-1}$ pesticide active ingredient and 0.7 kg $CO_2$-eq $kg^{-1}$ seed (Lal, 2004; Ghosh *et al*., 2021). Thus, the input and total related carbon footprint was calculated using Equation (8) and (9).

$$CF_{inputs} = (N \times EF_N) + (P \times EF_P) + (K \times EF_K) + (Pesticide \times EF_{Pesticide}) + (Seed \times EF_{Seed}) \quad \ldots (8)$$

$$CF_{total} = CF_{operations} + CF_{inputs} \quad \ldots (9)$$

To assess the efficiency of carbon utilization in crop production, carbon intensity (CI) indices were calculated for various biomass components. These indices offer a standardized metric for evaluating the overall carbon footprint in relation to the harvested yield of pods, shell, haulm and the entire biomass using Equation (10).

$$CI_j = \frac{\text{Total CF (Kg } CO_2 \text{ - eq } ha^{-1})}{Y_j (\text{kg } ha^{-1})} \quad \ldots (10)$$

Where

$CI_j$ = Carbon intensity of component. j (Pod, shell, haulm and total biomass).

$Y_j$ = Yield of the corresponding component expressed in kg $ha^{-1}$.

Accordingly, specific component wise carbon intensities such as pod, shell, haulm and biomass carbon intensity were calculated using Equations (11), (12), (13) and (14), respectively.

$$CI_{Pod} = \frac{\text{Total CF}}{\text{Pod yield (kg } ha^{-1})} \quad \ldots (11)$$

$$CI_{Shell} = \frac{\text{Total CF}}{\text{Shell yield (kg } ha^{-1})} \quad \ldots (12)$$

$$CI_{Haulm} = \frac{\text{Total CF}}{\text{Haulm yield (kg } ha^{-1})} \quad \ldots (13)$$

$$CI_{Biomass} = \frac{\text{Total CF}}{\text{Tital biomass (kg } ha^{-1})} \quad \ldots (14)$$

These indices provide a normalized measure of the emissions cost associated with each unit of agricultural output, thereby enabling the comparison of treatments not only in terms of total carbon footprint but also in terms of carbon use efficiency across crop components.

Data were collected on agronomic, physiological and carbon footprint parameters for treatments (T1-T8), including pod yield, haulm yield and groundnut morphology during 2022-2023. Energy inputs were measured through fuel consumption, machine time and labor for operations such as tillage, sowing, spraying, harvesting and pod stripping. Agricultural inputs were documented for energy and carbon-footprint calculations. Data were analyzed using ANOVA with a randomized block design, comparing treatment means by the LSD test at 1% significance ($p<0.01$). The carbon footprint was reported as emissions per hectare (kg $CO_2$-eq $ha^{-1}$) and carbon intensity (kg $CO_2$-eq $kg^{-1}$ output). Linear regression was used to analyze parameter relationships, with $R^2$ assessing the model fit. Analyses were performed using R software (4.5.1) and Python (Matplotlib/Seaborn) for figures.

## RESULTS AND DISCUSSION

### Rainfall monitoring and distribution trends during crop period of 2022 and 2023

The analysis of rainfall patterns in this study provided the necessary climatic context for evaluating the eight treatments (T1-T8) outlined in the Methods section. Understanding the spatial and temporal variations in rainfall during the crop period is crucial for assessing the effectiveness of water conservation treatments in semi-arid environments. The comparative regression analysis of monthly rainfall (Fig 1) from June to December in 2022 and 2023 demonstrated a consistently declining rainfall trend in both years and linear regression equations derived for each dataset are depicted in Fig 1. The equations revealed a negative correlation in both years during the latter half, with a steeper rainfall deceleration in 2022. The higher intercept of the 2022 model indicates that the June rainfall is more than 2023. Rainfall peaked at 260 mm in August 2022 and 178 mm in September 2023. Both years showed declining rainfall from October, reaching near zero by November 2023, with 2022 maintaining higher levels until December. The year 2023 was generally drier than that of 2022. The 2023 reduction may be attributed to El Niño conditions weakening monsoon intensity (Wang *et al.,* 2001), whereas 2022 likely experienced neutral or La Niña conditions enhancing rainfall (Ashok *et al.,* 2001). Local factors, such as land-use change and urbanization, may influence rainfall variability. Despite similar seasonal patterns, reduced rain volumes and gradual peak formation indicate interannual climate variability effects.

**Effect of *in situ* rainwater conservation practices on yield, morphological traits and energy indices of groundnut under semi-arid conditions**

The evaluation of eight conservation treatments (T1-T8) showed improvements in groundnut yield, haulm, RWUE and energy indices (Table 1). T8 (subsoiling + furrow diking), T6 (subsoiling + conservation furrow) and T7 (subsoiling + broad bed and furrow) outperformed the control (T1). T8 achieved the highest pod yield at 361.2 kg ha$^{-1}$, a 288% increase over T1 of 93 kg ha$^{-1}$. T6 and T7 yielded 313 and 281.6 kg ha$^{-1}$, respectively (Li *et al.,* 2020; Liang *et al.,* 2019). For haulm yield, T8 recorded at 2420 kg ha$^{-1}$, T6 at 2299 kg ha$^{-1}$ and T3 at 1744.5 kg ha$^{-1}$ and T1 recorded at 1445 kg ha$^{-1}$. RWUE was highest in T8 at 0.888 kg ha$^{-1}$ mm$^{-1}$, compared to T1 at 0.228 kg ha$^{-1}$ mm$^{-1}$. T7 and T6 showed values of 0.769 and 0.692 kg ha$^{-1}$ mm$^{-1}$, respectively (Kugedera *et al.,* 2022; Tefera *et al.,* 2024). The treatment effects were significant at p≤0.05. Superiority of T8 stemmed from enhanced infiltration and root development (Singh *et al*., 2019; Olayinka *et al*., 2021; Veeramani *et al*., 2025). The yield distribution (Fig 2) showed that T8 contributed 20.3% of the total production, T7 at 17.6% and T6 at 15.9%, whereas T1 contributed 5.2% (Kumar *et al.,* 2020; Rockström *et al.,* 2010). T8 achieved the highest plant height (40 cm), density (26 plants m$^{-2}$) and root length (13 cm) (Fig 3). T6 showed the highest plant density (28 plants m$^{-2}$), whereas T7 had the longest root length (14 cm). T1 showed the poorest performance (17 plants m$^{-2}$, 32 cm height, 8 cm root length). Statistical analysis confirmed significant differences in CV for plant density (12.5%), height (9.8%) and root length (11.4%).

The assessment of energy inputs and outputs across the treatments (T1-T8) showed the impact of rainwater conservation on groundnut yield and energy efficiency (Table 1). The energy input for field operations ranged from 2352 to 4081 MJ ha$^{-1}$, with land preparation requiring the most energy. Treatments with extensive mechanization (T2, T7, T8 and T6) required higher energy inputs (7387-7687 MJ ha$^{-1}$) owing to the larger machinery. T8 achieved the highest energy output (47,717 MJ ha$^{-1}$), followed by T7

**Table 1:** Impact of *In-situ* rainwater conservation practices on groundnut yield components and energy indices in semi-arid conditions.

| Treatments | Pod yield (kg ha$^{-1}$) | Haulm yield (kg ha$^{-1}$) | Rainwater use efficiency (kg ha$^{-1}$ mm$^{-1}$) | Shelling percentage | Energy output (MJ ha$^{-1}$) | Energy ratio (%) | Specific energy (MJ kg$^{-1}$) | Energy productivity (kg MJ$^{-1}$) | Net energy return (MJ ha$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| T1 | 93.0 | 1445.0 | 0.228 | 57.0 | 26500 | 4.5 | 63.3 | 0.016 | 20614 |
| T2 | 144.9 | 1698.6 | 0.356 | 62.0 | 31683 | 4.16 | 52.6 | 0.019 | 24068 |
| T3 | 169.2 | 1744.5 | 0.416 | 62.0 | 32792 | 5.8 | 33.4 | 0.03 | 27134 |
| T4 | 178.7 | 1727.2 | 0.440 | 67.0 | 32562 | 5.7 | 32.3 | 0.031 | 26860 |
| T5 | 233.4 | 1704.5 | 0.574 | 65.0 | 32295 | 5.7 | 31.9 | 0.04 | 26593 |
| T6 | 281.6 | 2299.0 | 0.692 | 67.0 | 34254 | 4.63 | 20.6 | 0.037 | 26823 |
| T7 | 313.0 | 1615.2 | 0.769 | 73.0 | 43536 | 5.9 | 26.3 | 0.042 | 36149 |
| T8 | 361.2 | 2420.0 | 0.888 | 70.0 | 47717 | 6.4 | 31.9 | 0.048 | 40286 |
| CD (5%) | 64.71 | 347.33 | 0.204 | 1.478 | 209.45 | NS | 15.35 | NS | 13927 |
| CV | 11.92 | 7.48 | 1.404 | 0.935 | 17.07 | 13.592 | 13.05 | 12.34 | 15.927 |
| SEM (±) | 7.088 | 2.04 | 0.29 | 0.375 | 0.74 | 0.526 | 0.97 | 0.45 | 6.32 |

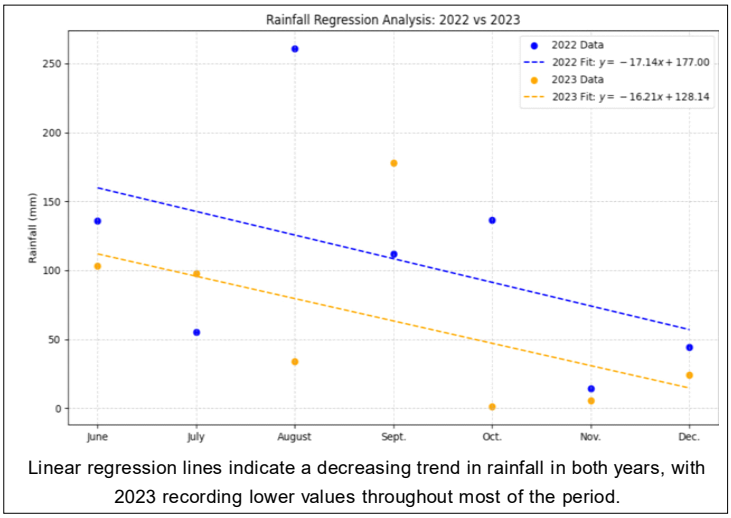



**Fig 1:** Comparison of monthly rainfall (mm) from June to December for the years 2022 and 2023.

(43,536 MJ ha$^{-1}$) and T6 (34,254 MJ ha$^{-1}$), whereas T1 had the lowest (26,500 MJ ha$^{-1}$). Superior performance of T8 resulted from the combination of subsoiling and furrow diking, which improved soil structure and moisture retention during critical growth stages, consistent with the findings of Rockström *et al.* (2010) and Tadesse *et al.* (2020). Conservation treatments enhance vegetative growth and moisture management. The energy ratios were highest in T8 (6.4%), T7 (5.9%) and T3 (5.8%), with T1 having the lowest ratio at 4.5%. T6 showed the lowest specific energy (20.6 MJ kg$^{-1}$) compared to T1 (63.3 MJ kg$^{-1}$). T8 achieved the highest energy productivity (0.048 kg MJ$^{-1}$) and net energy return (40,286 MJ ha$^{-1}$). These results demonstrate that integrated subsoiling and furrow-based strategies optimize biological and energy productivity in rainfed semi-arid systems (Oweis *et al.,* 2012; Yadav *et al*., 2017).

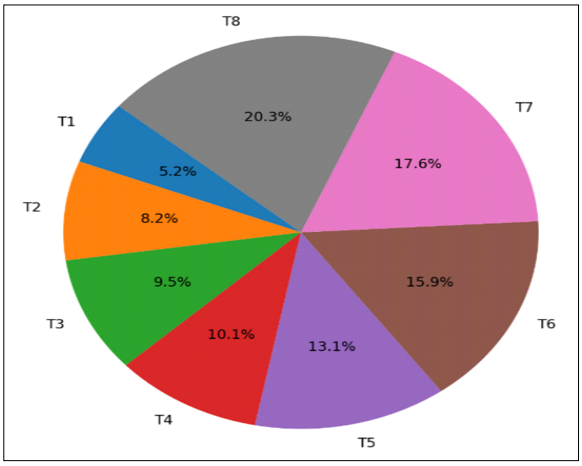



**Fig 2:** Share of groundnut pod yield among the treatments.

**Assessment of carbon footprint and carbon intensity indices in relation to crop yield**

Pod CF values ranged from 524.8 ± 11.44 kg $CO_2$-eq ha$^{-1}$ (T1) to 864.5±58.35 kg $CO_2$-eq ha$^{-1}$ (T2) (Table 2). The shell CF varied between 209.9±4.58 (T1) and 345.8±23.34 (T2), while the haulm CF ranged from 501.6 to 794.7 kg CO, -eq ha$^{-1}$. The total biomass CF was lowest in T1 (532.3±49.2) and highest in T2 (863.3±62.8), with high-yield treatments (T6-T8) maintaining high CF values. The high CF under T2, despite moderate yield increases, indicates that early

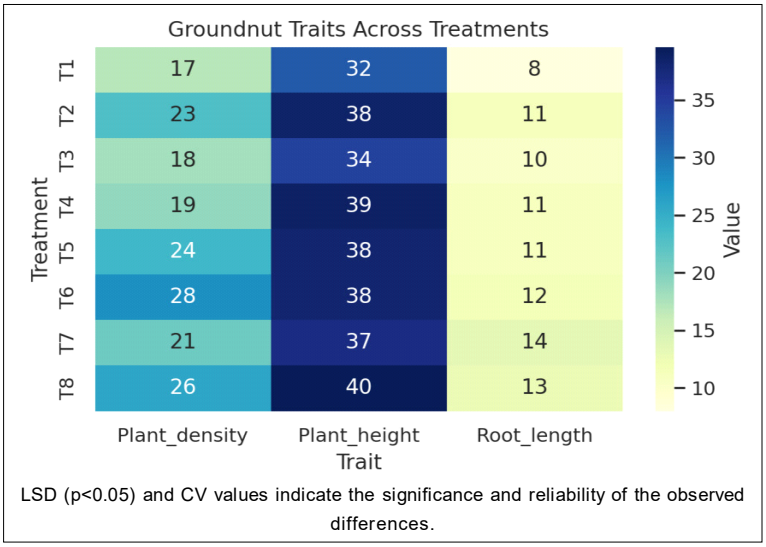


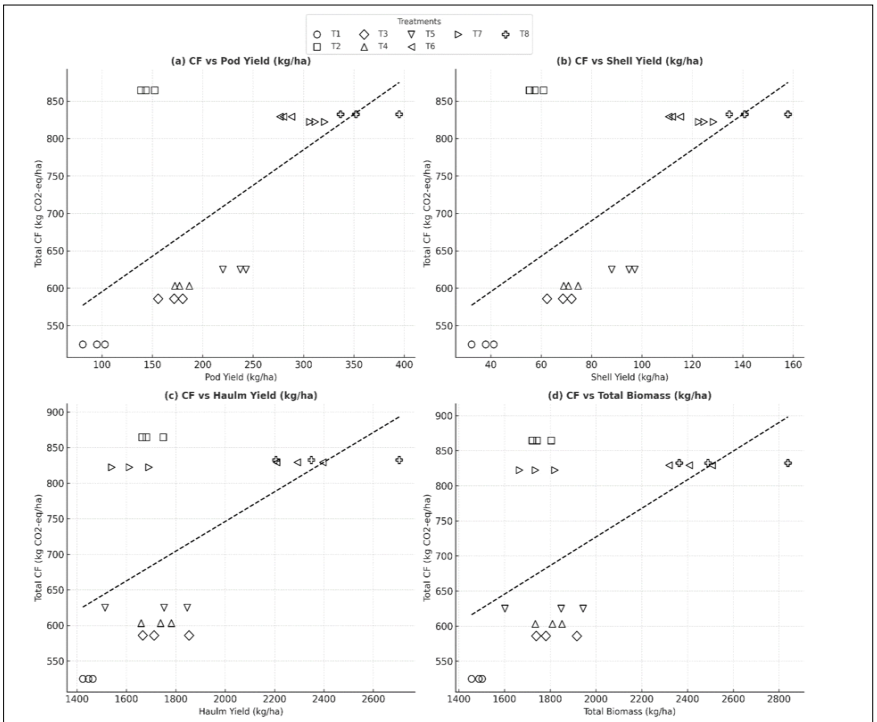

**Fig 3:** Heatmap depicting the effect of treatments (T1-T8) on plant density, plant height and root length in groundnut.

**Table 2:** Carbon footprint indices (mean±SD) for pod, shell, haulm and total biomass across treatments.

| Treatment | Pod yield (kg ha$^{-1}$) | Shell yield (kg ha$^{-1}$) | Haulm yield (kg ha$^{-1}$) | Biomass yield (kg ha$^{-1}$) | Pod CF (kg $CO_2$ -eq ha$^{-1}$) | Shell CF (kg $CO_2$ -eq ha$^{-1}$) | Haulm CF (kg $CO_2$ -eq ha$^{-1}$) | Biomass CF (kg $CO_2$ -eq ha$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| T1 | 93.0 | 37.2 | 1445.0 | 1482.2 | 524.8±11.44$^{d}$ | 209.9±4.58$^{d}$ | 501.6±44.4$^{c}$ | 532.3±49.2$^{d}$ |
| T2 | 144.9 | 58.0 | 1698.6 | 1756.6 | 864.5±58.35$^{a}$ | 345.8±23.34$^{a}$ | 794.7±50.6$^{a}$ | 863.3±62.8a |
| T3 | 169.2 | 67.7 | 1744.5 | 1812.2 | 585.9±22.85$^{cd}$ | 234.4±9.14$^{cd}$ | 531.2±49.8$^{c}$ | 584.4±54.2$^{cd}$ |
| T4 | 178.7 | 71.5 | 1727.2 | 1798.7 | 603.1±4.14$^{c}$ | 241.2±1.66$^{c}$ | 549.3±19.5$^{c}$ | 605.6±21.3$^{c}$ |
| T5 | 233.4 | 93.4 | 1704.5 | 1797.9 | 624.9±18.11$^{c}$ | 249.9±7.24$^{c}$ | 549.7±51.6$^{c}$ | 627.8±46.8$^{c}$ |
| T6 | 281.6 | 112.7 | 2299.0 | 2411.6 | 829.2±58.67$^{ab}$ | 331.7±23.47$^{ab}$ | 734.8±43.6$^{ab}$ | 823.4±49.7$^{ab}$ |
| T7 | 313.0 | 125.2 | 1615.2 | 1740.4 | 822.3±17.95$^{ab}$ | 328.9±7.18$^{ab}$ | 680.6±24.1$^{b}$ | 817.8±29.1$^{ab}$ |
| T8 | 361.2 | 144.5 | 2420.0 | 2564.5 | 832.4±20.72$^{ab}$ | 333.0±8.29$^{ab}$ | 707.4±27.8$^{ab}$ | 824.2±25.9$^{ab}$ |

Different superscript letters within a column indicate significant differences at p<0.01.

intensification leads to disproportionate emissions. High-yield treatments showed higher absolute CF but demonstrated better carbon efficiency per-unit yield. Similar patterns occur in cereal-legume systems, where intensification increases emissions while improving efficiency (Burney *et al.*, 2010). Regression analysis showed a strong positive relationship between CF and yield components (Fig 4). As the yield increased, there was a notable reduction in carbon intensity (CI) values (Table 3). Specifically, the CI for pods decreased from 5.70±0.71 kg $CO_2$-eq $kg^{-1}$ in T1 to 2.32±0.19 kg $CO_2$-eq $kg^{-1}$ in T8, while the CI for shells declined from 14.25±1.77 to 5.79±0.47 kg $CO_2$ -eq $kg^{-1}$ across all treatments. Similar downward trends were observed for the CI of haulm and biomass. Regression models indicated negative linear correlations between CI and yield parameters (Fig 5). The shell yield showed the steepest reduction (slope = -0.062), followed by pods (-0.011), while biomass and haulm had gentler slopes, indicating the role of reproductive yield in decreasing CI. High $R^2$ values (>0.87) indicate that yield performance predicts CI outcomes, consistent with legume systems (Goglio *et al.,* 2018). While yield intensification increases CF, it reduces CI, creating a productivity-emission trade-off. T6-T8 achieved the highest yields and lowest CI values, suggesting that productivity gains diluted maintenance emissions (Goglio *et al.,* 2018; Nemecek *et al.,* 2015).



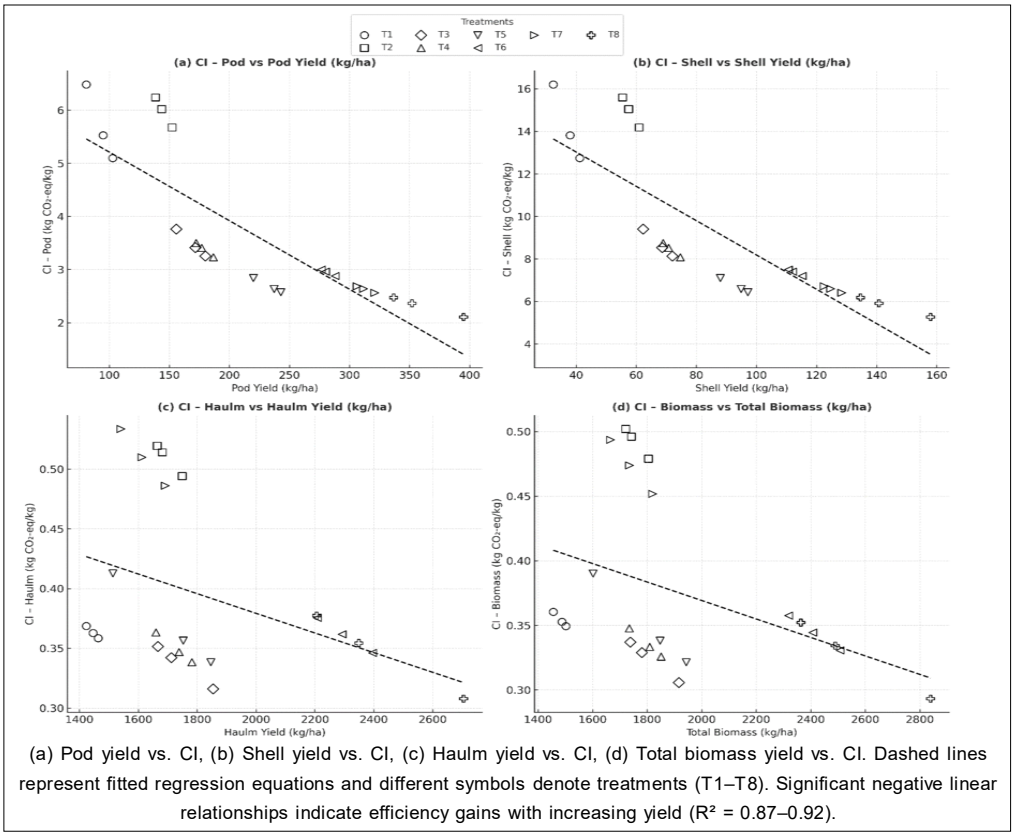

(a) Pod yield vs. CF, (b) Shell yield vs. CF, (c) Haulm yield vs. CF, (d) Total biomass yield vs. CF. Dashed lines represent fitted regression equations and different symbols denote treatments (T1-T8). Strong positive linear relationships were observed across all components ($R^2$ = 0.82–0.88).

**Fig 4:** Regression relationships between yield components and carbon footprint (CF) across treatments.

**Table 3:** Carbon intensity indices (mean±SD) for pod, shell, haulm and total biomass across treatments.

| Treatment | Pod yield (kg $ha^{-1}$) | Shell yield (kg $ha^{-1}$) | Haulm yield (kg $ha^{-1}$) | Biomass yield (kg $ha^{-1}$) | Pod CI (kg $CO_2$ -eq $ha^{-1}$) | Shell CI (kg $CO_2$ -eq $ha^{-1}$) | Haulm CI (kg $CO_2$ -eq $ha^{-1}$) | Biomass CI (kg $CO_2$ -eq $ha^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| T1 | 93.0 | 37.2 | 1445.0 | 1482.2 | 5.70±0.71$^{c}$ | 14.25±1.77$^{c}$ | 0.36±0.01$^{a}$ | 0.35±0.01$^{a}$ |
| T2 | 144.9 | 58.0 | 1698.6 | 1756.6 | 5.98±0.28$^{c}$ | 14.94±0.71$^{c}$ | 0.51±0.01$^{b}$ | 0.49±0.01$^{b}$ |
| T3 | 169.2 | 67.7 | 1744.5 | 1812.2 | 3.48±0.26$^{b}$ | 8.69±0.65$^{b}$ | 0.34±0.02$^{a}$ | 0.32±0.02$^{a}$ |
| T4 | 178.7 | 71.5 | 1727.2 | 1798.7 | 3.38±0.14$^{b}$ | 8.45±0.34$^{b}$ | 0.35±0.01$^{a}$ | 0.34±0.01$^{a}$ |
| T5 | 233.4 | 93.4 | 1704.5 | 1797.9 | 2.68±0.14$^{a}$ | 6.71±0.35$^{a}$ | 0.37±0.04$^{a}$ | 0.35±0.04$^{a}$ |
| T6 | 281.6 | 112.7 | 2299.0 | 2411.6 | 2.95±0.06$^{a}$ | 7.36±0.15$^{a}$ | 0.36±0.01$^{a}$ | 0.34±0.01$^{a}$ |
| T7 | 313.0 | 125.2 | 1615.2 | 1740.4 | 2.63±0.06$^{a}$ | 6.57±0.16$^{a}$ | 0.51±0.02$^{b}$ | 0.47±0.02$^{b}$ |
| T8 | 361.2 | 144.5 | 2420.0 | 2564.5 | 2.32±0.19$^{a}$ | 5.79±0.47$^{a}$ | 0.35±0.04$^{a}$ | 0.33±0.03$^{a}$ |

Different superscript letters within a column indicate significant differences at p<0.01.




(a) Pod yield vs. CI, (b) Shell yield vs. CI, (c) Haulm yield vs. CI, (d) Total biomass yield vs. CI. Dashed lines represent fitted regression equations and different symbols denote treatments (T1–T8). Significant negative linear relationships indicate efficiency gains with increasing yield ($R^2$ = 0.87–0.92).

**Fig 5:** Regression relationships between yield components and carbon intensity (CI) across treatments.

The positive CF-yield correlation across pods, shell, haulm and biomass indicates that higher yields require increased inputs, elevating emissions (Lal, 2020). Pod CI decreased from 5.70 kg $CO_2$-eq $kg^{-1}$ in T1 to 2.32 kg $CO_2$-eq $kg^{-1}$ in T8, showing 60% reduced emissions. Shell yield showed the steepest CF regression slope, whereas pod yield showed the largest CI reduction. These findings indicate that optimizing inputs for higher yields enables carbon-efficient agriculture (Tilman *et al.,* 2011; Burney *et al.,* 2010).

## CONCLUSION

This study demonstrated that mechanized in-situ rainwater conservation techniques significantly improved groundnut yield, rainwater use efficiency and energy performance in semi-arid regions. The combination of subsoiling with furrow diking (T8) was the most effective, achieving the highest pod and haulm yields, superior energy ratios and greatest net energy returns. Other treatments, such as subsoiling with conservation furrows (T6) or broad bed and furrow (T7), also exhibited notable improvements compared with the control. Carbon footprint analysis revealed that although high-yield treatments increased total emissions per hectare, they reduced carbon intensity (CI), highlighting a trade-off between productivity and emission efficiency. Regression models indicated a strong positive relationship between yield and carbon footprint, with carbon intensity significantly decreasing as the yield increased, particularly for pods and shells. In summary, integrated mechanized practices, especially subsoiling with furrow diking, offer a sustainable intensification approach for rainfed groundnut farming, enhancing food and fodder productivity while promoting energy efficiency and carbon-mitigation objectives.

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### Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for direct or indirect losses resulting from the use of this content.

### Informed consent

Not applicable. This study did not involve human or animal subjects.

### Authors contribution

Kishore Nalabolu: Conceptualization, experimental design, field investigation, data curation, statistical analysis and manuscript drafting; Ch. Ratna Raju: Methodology development, irrigation and water conservation inputs and review of

results; D. Srigiri: Data collection, field management and validation of experimental protocols; V. Shobhan Naik: Support in farm machinery operation, field experimentation and data interpretation; K. Arun Kumar: Agronomic management, crop observations and contribution to result validation; B.V. Mohana Rao: Supervision, critical review and editing of the manuscript, ensuring methodological and technical accuracy.

### Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding body or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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