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Integrating technologies in groundnut (Arachis hypogaea L.) – A novel case study for enhancing its productivity, cost-effectiveness and quality aspects across varieties and growing seasons in Gujarat Plains of India

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Integrating technologies in groundnut (*Arachis hypog*aea L.) – A novel case study for enhancing its productivity, cost-effectiveness and quality aspects across varieties and growing seasons in Gujarat Plains of India

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Abstract

Tremendous yield gap exists between realization of actual *vis-à-vis* potential yield of groundnut crop, as research and development efforts have bridged this gap partially and not fully, as far as current trend of technology-adoption is concerned (in reference to matching the potential and farmer-level yields of the crop). Despite scientific advancements, the adoption of site-specific technologies remains inadequate due to scattered and incomplete information gathered on integrating diverse and versatile farming interventions/practices. Therefore, strategic action is inevitable in amalgamating these, many a time this being local/region-specific, technological integration under existing agro-ecology. In this context, our study aimed at enhancing groundnut yield through integration of available, time-tested and cost-effective Best (crop) Management Practices (BMPs) in semi-arid conditions of the Indian State of Gujarat during 2022 and 2023 spring-summer and rainy seasons to maximize realization of productive potential of the crop. The experiment evaluated three management practices as treatments, *viz.*,1) Farmers' practice (control), 2) Progressive farmers' practices, and 3) Integrated Crop Management (ICM) practices, using both (Habit groups of) Spanish Bunch ('TG-37A') and Virginia Bunch ('KDG-128') varieties. ICM included rhizobia, plant growth promoting rhizobia (PGPR), FYM, NPK, gypsum, and *Trichoderma viride*, while progressive farmers' practices involved higher inputs of FYM, NPK, micronutrients, and plant protection measures. Farmers' practice (control) is the practice adapted by a small and marginal farmer (< 2 hectares of arable land) under moderate resource-constraints condition. The study demonstrated that ICM practices had enhanced crop yields and higher economic returns under both the cultivars across the growing seasons. During spring-summer, pod yield for TG-37A increased from 2925 kg/ha in 2022 to 3182 kg/ha in 2023, while KDG-128 recorded higher yields of 3625 kg/ha and 3923 kg/ha, respectively during the same period. Varietal supremacy was evident, as KDG-128 consistently outperformed TG-37A, in respect of multiple attributes (net returns in the range of ₹1,82,453–1,97,079/ha, and benefit-cost ratio (BCR) of 4.41–4.68), compared to TG-37A (with net returns of ₹1,29,875–1,50,716/ha and BCR of 3.48–3.88). Similar trends were observed during rainy season, though with comparatively lower yields. Although moisture, oil, and protein contents in the kernels did not vary significantly among treatments, ICM plots had higher uptake of nutrients (N, P, and K) and superior quality attributes compared to other management practices. The study concluded that ICM practices could help in improving crop yield, nutrient uptake, and economic returns, and the responses were differed with

plant types (Virginia bunch 'KDG-128' outperforming Spanish bunch 'TG-37A') and seasons (Higher productivity realized during spring-summer compared to rainy season), which further highlights the effectiveness of ICM in realizing stable groundnut productivity in the country as a whole (2260 kg/ha). PGPR - NutBoost emerged as a promising option for sustainable crop production, improved nutrient recovery, and long-term soil health enhancement. Future research needs should endeavour in integrating the best and popular genotype under seed-chain with compatible BMPs balancing specific agroecological constraints for realization of genetic potential yield of the crop.

Keywords: Biofertilizers, Farmers' practice, Gypsum, ICM practice, PGPR-NutBoost, Progressive farmers' practice, *Trichoderma viride*

The increasing demand for food and energy, driven by population growth and rising incomes, underscores the need for sustainable agricultural practices. The Green Revolution in the latter half of the 20th century in the country was a significant success in boosting food production without major increases in crop area or food prices. However, many technologies central to the Green Revolution, such as increased use of fertilizers, pesticides, and irrigation, can negatively impact environmental quality and ecosystem services if not managed properly[1]. While high yields are essential for environmental protection, achieving them sustainably remains a challenge. The stagnation in yield growth of major crops, including oilseeds, highlights the need to identify whether this is due to diminishing yield gaps or factors such as soil degradation, pollution, and climate change [2].

Groundnut (*Arachis hypogaea*), an annual leguminous plant, is cultivated globally for its protein- and lipid-rich seeds and oil [3,4]. In India, groundnut is a major oilseed crop, contributing ~35% of total oilseed production, with an area of 5.351 million hectares, producing 12.091 million tonnes, and yielding an average dry pod yield of 2,260 kg/ha during 2025-26 [5]. Despite the largest cultivation area, India's groundnut productivity lags behind the United States and China, primarily due to 85% of the cultivation being rainfed and vulnerable to weather fluctuations. Additionally, groundnut is often grown in low-fertility, light-textured soils, which further reduces yields [6]. Though drought-tolerant, groundnut's nutrient requirements are high, and inadequate nutrient uptake often results in poor yields. Hence, effective nutrient management strategies amalgamating better management practices are necessary to improve groundnut productivity, which is crucial for ensuring food security and economic sustainability of the agroecology.

Nutrient management also plays a vital role in maximizing groundnut yields. Judicial use of fertilizers increases agricultural production while minimizing environmental pollution, as continuous reliance on chemical fertilizers deteriorates soil health and reduces productivity over time. Additionally, indiscriminate use of fertilizers results in low nutrient recovery, increased production costs, and environmental degradation [7]. Groundnut requires balanced mineral nutrition for optimal growth, yet farmers often apply insufficient or imbalanced fertilizers due to lack of adequate knowledge/adoption, leading to nutrient deficiencies and reduced yields [8]. Therefore, it

is critical to focus on optimizing mineral nutrition in groundnut cultivation and recommending suitable interventions/practices to enhance its productivity and profitability [9].

Recent research emphasizes the importance of integrated and biologically driven nutrient strategies - such as biofertilizers, PGPR consortia, micronutrient fortification, and organic amendments - to simultaneously enhance yield, improve soil health, and increase nutrient-use efficiency. Studies conducted across semi-arid regions have shown that integrated nutrient management (INM) and microbial inoculants significantly boost groundnut productivity, oil content, and nitrogen fixation capacity while also improving soil carbon pools and microbial activity. Emerging evidence further highlights that climate-smart nutrient management practices, including gypsum-based soil amendments and enhanced-efficiency of fertilizers, can reduce production risks under variable rainfall, making them highly relevant for India's predominantly rainfed groundnut or groundnut based cropping systems. Collectively, these advancements reflect a shift toward more sustainable, resource-efficient, and biologically informed approaches that address yield stagnation and soil degradation while contributing to long-term resilience of groundnut-based cropping systems.

Research and development efforts must bridge the yield gap between research station potential and farmer-level yields. Despite advancements in technological innovations, the adoption of recommended production technologies remains limited due to scattered and incomplete information acquired on farming practices. Therefore, for bridging the yield gaps, a holistic evaluation of different practices, including Farmers' Practices (Large gaps), Progressive Farmers' Practices (Medium gaps), and Integrated Crop Management (ICM-small gaps or no gap), is essential to assess their impact on nutrient availability, uptake, yield, and economic returns. The Saurashtra region of South Gujarat, where groundnut cultivation dominates, served as a case study to explore improved scientific nutrient management practices, highlighting the importance of addressing nutrient management gaps for sustainable groundnut production. It was hypothesized that ICM practices, integrating PGPR, balanced fertilization, and soil amendments, would significantly enhance growth, nutrient uptake, yield, and profitability compared to farmers' and even progressive farmers' practices. The specific objectives of the study were to (i) compare growth, yield, quality, and nutrient uptake of groundnut under three management practices, (ii) assess seasonal performance of two varieties (TG 37A and KDG 128), and (iii) evaluate the economic viability of each practice to identify the most efficient and sustainable nutrient management strategy.

Materials and Methods

The field experiment was conducted at the ICAR-Indian Institute of Groundnut Research (IIGR), Junagadh, Gujarat, during the spring-summer and rainy seasons of 2022 and 2023. The site is located at the foothills of Mount Girnar, at 21.31° N latitude and 70.36° E longitude, with an altitude of 60 m above mean sea level (Fig 1). It falls under the *Southern Saurashtra Agro-climatic Region* of the state of Gujarat and the *Gujarat Plain and Hill Region* of India. The soil properties and climatic conditions of the experimental site is given in Table 1. The environmental condition

in respect of Temperature, rainfall and evaporation is given in Fig 2 representing spring-summer (Feb –Jun) and rainy (Jun-Sept) seasonal weather condition during 2023. More or less similar weather conditions prevailed during spring-summer and rainy seasons of 2022 with little deviations.

Fig 1: Experimental site



Table 1: Soil Properties and Climatic Conditions of the Experimental Site

Parameter	Value	Method / Reference
Soil type	Calcareous medium black clayey (*Vertic Ustrochrept*)	Soil Taxonomy [10]
Soil pH	8.24 (alkaline)	pH meter (1:2.5 soil: water) [11]
Organic carbon (%)	0.63% (medium)	Walkley–Black Wet Oxidation [12]
Available Nitrogen (kg/ha)	182 kg/ha (low)	Alkaline $KMnO_4$ method [13]
Available Phosphorus (kg/ha)	7.95 kg/ha (low)	Bray No.1 / Olsen method depending on [14]
Available Potassium (kg/ha)	96.88 kg/ha (low)	Neutral normal ammonium acetate extraction [11]
Bulk Density (g/cc)	1.44 (0–15 cm), 1.46 (15–30 cm)	Core method [15]
Field Capacity (%)	30.4% (0–15 cm), 30.3% (15–30 cm)	Pressure plate apparatus [16]
Permanent Wilting Point (%)	14.4% (0–15 cm), 14.0% (15–30 cm)	Pressure plate apparatus [16]
Rainfall during crop period (mm)	1214.4 mm	Standard rain gauge recording
Number of rainy days	45 days	Standard meteorological observations (IMD guidelines)*
Winter rainfall	13.3 mm over 2 days	Standard meteorological observations (IMD guidelines)*

*Indian Meteorological Department (IMD)

Fig 2: Weather condition during spring-summer and rainy seasons at the location

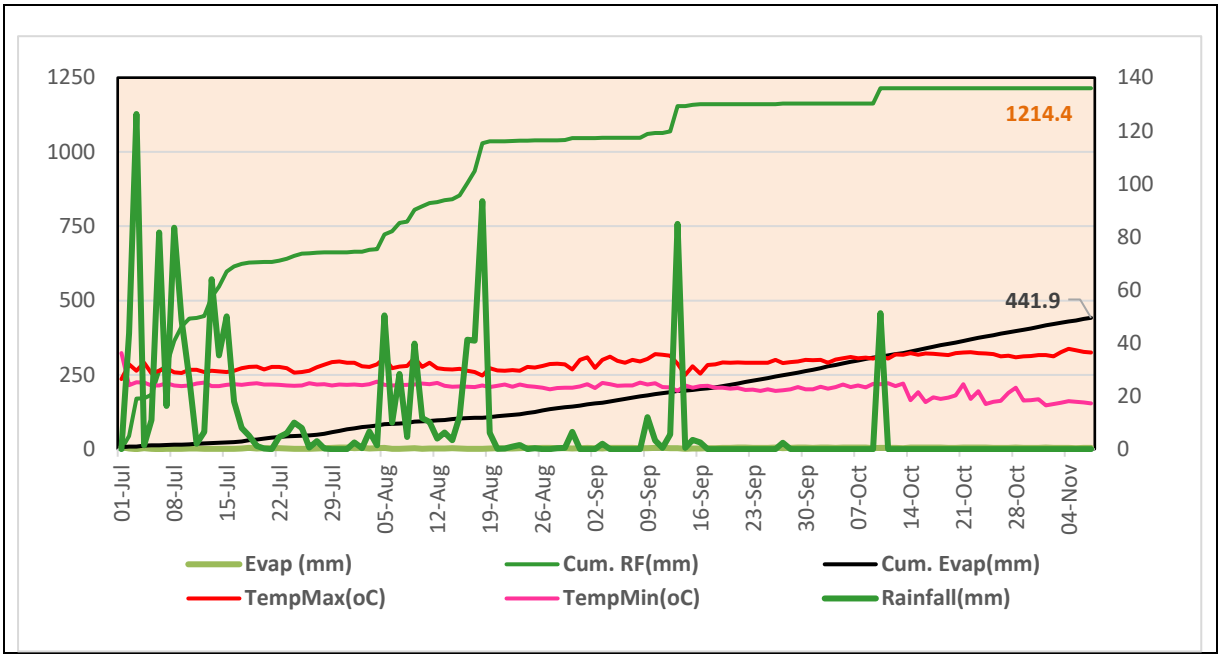


Fig 2A. Weather situation at the Site in Junagadh, Gujarat (India) during Rainy 2022



Fig 2B. Weather situation at the site in Junagadh, Gujarat (India) during spring-summer 2023 with similar pattern (meagre rainfall) during Spring-summer 2022

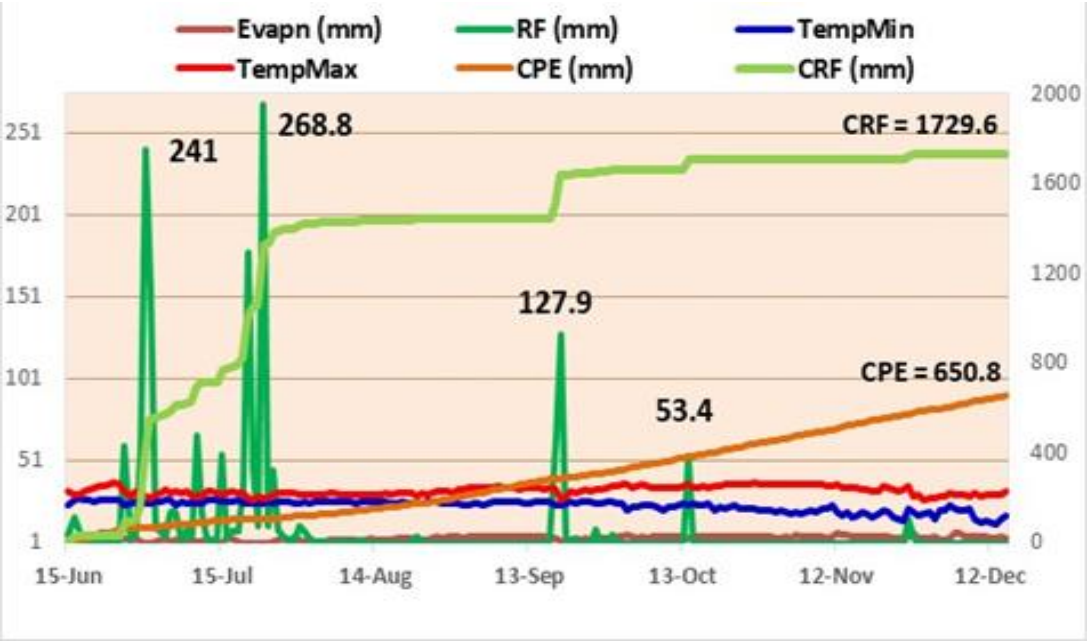


Fig 2C. Weather situation at the Site in Junagadh, Gujarat (India) during Rainy 2023

The experiment consisted of three distinct treatments based on management practices on package mode in groundnut (*viz*., 1) Farmers' practice (FP) as a Control, 2) Practice adopted by the Progressive Farmers (PFP), and 3) ICM Practice (ICMP) taken up by the research institution as the recommended practice) along with two groundnut varieties (TG- 37A -Spanish Bunch) and KDG-128 (Virginia Bunch). The details of practices followed in various treatments under different management practices are presented in Table 2. These treatments were laid out in four times replicated Randomized Complete Block Design (RCBD) and grown in large plots (>90 m^2) during both the seasons.

TG-37A, released by BARC, Trombay (Maharashtra State of India), in 2004, is suitable for rainy and rabi-summer seasons across the states of Gujarat, Rajasthan, and Uttar Pradesh. It matures in 105–110 days, yielding 2080 kg/ha (rainy) and 2840 kg/ha (rabi-summer) of pods, with a shelling percentage of 64%, 48% oil content, and 100-kernel mass of 39g. It is resistant to collar rot, rust, and late leaf spot diseases, with 15-day seed dormancy. KDG-128, developed by MPKV, Digraj (Maharashtra State of India), and released in 2016, is recommended for rainy season cultivation in the states of Tamil Nadu, Andhra Pradesh, Karnataka, Southern Maharashtra, Gujarat, and Rajasthan. It matures in 113 days, yielding 2425 kg/ha of pods, with 65% shelling, 50.9% oil content, and moderate resistance to rust and leaf spot.

The details of the package of practices followed in various treatments under different management or farming practices are presented in Table 2. The estimation of soil - N, P, K, OC, EC and pH in the experimental field under both the varieties were made before sowing of the spring-summer crop in 2022 and after harvesting of the rainy season crop in 2023. The observed values of weather

parameter are presented in Fig 2 for information about the weather condition prevailing at the location. The observations pertaining to growth and yield attributes, and production economics were also recorded for two varieties belonging to two different habit groups during all the seasons (spring-summer and rainy, 2022 & 2023).

The data obtained under different treatments with respect to various parameters were subjected to Analysis of Variance (ANOVA) for complete randomized block design using the general linear model (GLM procedure) of SPSS 16.0 software package [17,18]. The means (± standard error of mean) were tested for significant difference by using Tukey's b test. Before analysis of variance estimation, all data were subjected to test for homogeneity of error variances. Treatment means were compared using a protected least significant difference test at $p \leq 0.05$. Box and whisker plots of yield was prepared by SPSS 16.0 software while other graphs were prepared in Microsoft excel.

Table 2: Package of practices followed in various treatments under different management practices

Treatments	Particulars
Farmers' Practice	▪ Seed treatment with fungicides (Carbendazim + Mancozeb) mix well and dry before sowing ▪ Seed rate @ 130-150 kg/ha ▪ Soil application of DAP @ 150 kg/ha ▪ The 'Control plot' is applied with no FYM and without biocontrol agents ▪ Plant protection: As per trader's advice fungicide and insecticide are used and hand weeding is done, if required
Progressive Farmers' Practice	▪ Seed treatment with fungicides (Carbendazim + Mancozeb), insecticide (Imidacloprid), PSB, KSB and *Rhizobium* by spraying on seed, respectively; mix well and dry before sowing ▪ Seed rate @ 120-125 kg/ha ▪ Soil application of FYM @ 7-8 t/ha, 25-50-50 NPK kg/ha and foliar spray of multi micronutrient-mixture grade IV (25 g per 15 liters of water) at flowering & pod formation stage ▪ Bio control – apply *Trichoderma viride* @ 2.5 kg/ha with 500 kg FYM ▪ Plant protection: Recommended fungicides, insecticides and herbicides, if required
ICM Practice	▪ Seed treatment with *Rhizobium*, IGR 6 or IGR 40 at 1.25 kg/ha and PGPR 'NUTBOOST' at 1.25 kg/ha mix well and dry before sowing ▪ Seed rate @120 kg/ha ▪ Soil application of FYM @ 5 t/ha, 25-50-25 NPK kg/ha (100% N and P & 50% K as basal and 50% K at 45 DAS), Gypsum @ 500 kg/ha (50% as a basal and 50% at 45 DAS) and foliar application of multi micronutrient-mixture grade IV (25 g per 15-liter water) at flowering and pod formation stages ▪ Bio control – apply *Trichoderma viride* @ 2.5 kg/ha (amalgamated with 500 kg of FYM/ha) ▪ Plant protection: Recommended fungicides, insecticides and herbicides, as and when required

Results

Growth and development parameters

The growth and nodulation characteristics of groundnut cultivars 'TG-37A' and 'KDG-128' varied significantly under different management practices during the spring-summer and rainy seasons (Table 3). During the spring-summer season, plant height of TG-37A increased from 31.8 cm under Farmers' Practice to 32.8 cm under Progressive Farmers' Practice and 33.7 cm under ICM Practice **(**+3.1% and +6.0%**,** respectively), whereas plant height of KDG-128 (38.4–39.7 cm) remained statistically unaffected. The number of branches per plant in TG-37A was significantly higher under ICM Practice (4.03 branches plant^{-1}) compared to Farmers' Practice (3.10 branches plant^{-1}**;** +30.0%), while Progressive Farmers' Practice recorded 3.43 branches plant^{-1} **(**+10.6%**).** In contrast, branch number in KDG-128 (5.79–5.97 plant^{-1}) did not differ significantly among practices. Nodule count during spring-summer increased markedly under ICM Practice, reaching 116.2 nodules plant^{-1} in TG-37A and 205.0 nodules plant^{-1} in KDG-128, representing increases of 43.0% and 23.5%, respectively, over Farmers' Practice (81.25 and 166.0 nodules plant^{-1}). Progressive Farmers' Practice also enhanced nodule count to 97.4 and 195.5 nodules plant^{-1} in TG-37A and KDG-128 (+19.9% and +17.8%**,** respectively). Correspondingly, nodule dry weight increased under ICM Practice to 33.0 mg plant^{-1} (TG-37A) and 58.9 mg plant^{-1} (KDG-128) compared with 28.3 and 50.4 mg plant^{-1} under Farmers' Practice (+16.6% and +16.9%**,** respectively). During the rainy season, plant height of both cultivars was not significantly influenced by management practices, though ICM Practice recorded marginally higher values (29.9 and 30.6 cm) compared to Farmers' Practice (29.6 and 28.4 cm). The number of branches per plant in TG-37A remained statistically similar across treatments (3.55–4.62 plant^{-1}), whereas in KDG-128, ICM Practice increased branch number to 5.32 plant^{-1} compared with 5.25 plant^{-1} under Farmers' Practice (+14.7%**).** Nodule count during rainy was significantly higher under ICM Practice, registering 155.5 nodules plant^{-1} in TG-37A and 218.9 nodules plant^{-1} in KDG-128, which corresponded to increases of 25.2% and 32.6%, respectively, over Farmers' Practice (124.2 and 165.1 nodules plant^{-1}). Similarly, nodule dry weight was markedly enhanced under ICM Practice to 58.8 mg plant^{-1} (TG-37A) and 71.8 mg plant^{-1} (KDG-128) compared with 39.0 and 53.1 mg plant^{-1} under Farmers' Practice (+50.8% and +35.2%**,** respectively). Thus, ICM Practice had an advantage across the seasons and varieties compared to both Farmers' and Progressive Farmers' Practices.

Yield and Yield attributes

The yield attributes and yield of groundnut cultivars 'TG-37A' and 'KDG-128' were significantly influenced by different management practices during both spring-summer and rainy seasons (Tables 4-5). Across seasons, KDG-128 consistently outperformed TG-37A. Among the practices, ICM Practice recorded the highest yield attributes, with pods per plant increasing to 19.0–15.6 in TG-37A (+31.9–30.0%) and 22.8–20.2 in KDG-128 (+41.6–30.3%) during spring-summer and rainy, respectively, over Farmers' Practice. Similarly, seed index and shelling percentage were

highest under ICM, with seed index increasing by 10.1–16.8% and shelling percentage by 3.3–6.4% over Farmers' Practice. Consequently, pod yield under ICM Practice increased significantly, reaching 3055 and 2037 kg ha^{-1} in TG-37A (+19.6 and +18.5%) and 3774 and 2911 kg ha^{-1} in KDG-128 (+18.8 and +19.7%) during spring-summer and rainy seasons, respectively. Average pod yield (kg/ha) of TG37A and KDG128 under different farming practices over the seasons of study (spring-summer 2022 to rainy 2023) is presented in Fig. 3. Kernel yield followed a similar trend, with ICM recording 2126–1453 kg ha^{-1} in TG-37A (+27.2–25.0%) and 2748–2071 kg ha^{-1} in KDG-128 (+26.1–23.6%) over Farmers' Practice. Total yield was also highest under ICM, increasing by 17.5–16.7% in TG-37A and 19.3–18.0% in KDG-128. Haulm yield showed a consistent increase under ICM Practice, although differences were non-significant during spring-summer in TG-37A. Harvest index remained unaffected by farming practices across seasons. Thus, both yield and yield attributes were varied under various management practices both during the spring-summer and rainy seasons (Table 4-5). Invariably, ICM Practice had an edge across the seasons and varieties.

Table 3: Growth parameters of groundnut cultivars 'TG-37A' and 'KDG-128' as influenced by farming practices during Spring-Summer and *Rainy seasons* (values represent pooled data of 2022 and 2023)

Treatment	Plant height (cm)				Branches/plant (No./pl)				Nodule count (No./pl)				Nodule dry wt. (mg/pl)			
	Spring-Summer		Rainy		Spring-Summer		Rainy		Spring-Summer		Rainy		Spring-Summer		Rainy	
	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128
Farmers' Practice	31.8^{b}	38.4^{a}	29.6^{a}	28.4^{a}	3.10^{b}	5.79^{a}	3.55^{b}	5.25^{a}	81.25^{c}	166.0^{c}	124.2^{c}	165.1^{c}	28.3^{b}	50.4^{b}	39.0^{c}	53.1^{c}
Progressive Farmers' Practice	32.8^{a}	39.1^{a}	29.0^{a}	29.5^{a}	3.43^{b}	5.87^{a}	3.87^{b}	5.12^{a}	97.4^{b}	195.5^{b}	139.7^{b}	186.2^{b}	30.8^{a}	57.0^{a}	50.4^{b}	62.2^{b}
ICM Practice	33.7^{a}	39.7^{a}	29.9^{a}	30.6^{a}	4.03^{a}	5.97^{a}	4.62^{a}	5.32^{a}	116.2^{a}	205.0^{a}	155.5^{a}	218.9^{a}	33.0^{a}	58.9^{a}	58.8^{a}	71.8^{a}
CD (p=0.05)	**	NS	NS	NS	***	NS	**	NS	***	**	**	***	**	**	***	**

Note: NS: Nonsignificant; * Significant at <0.05; ** Significant at <0.01; *** Significant at <0.001 (Statistical significance at 95%, 99%, and 99.9%, respectively that represents increasing levels of confidence that research results are not due to chance, corresponding to 5%, 1%, and 0.1% risks of false positives (p-values of 0.05, 0.01, 0.001). Higher confidence levels provide stronger evidence but result in wider confidence intervals, reducing precision. Superscript letters (a,b,c…) denotes statistical similarity (for same letter) and dissimilarity (different letters). Pl. refers to Plant.

Table 4: Yield attributes of groundnut cultivars 'TG-37A' and 'KDG-128' as influenced by farming practices during Spring-Summer and Rainy (values represent pooled data of 2022 and 2023)

Treatment	Pods/plant (no./pl)				Seed Index (g)				Shelling per cent (%)			
	Spring-Summer		Rainy		Spring-Summer		Rainy		Spring-Summer		Rainy	
	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128
Farmers' Practice	14.4^{b}	16.1^{c}	12.0^{c}	15.5^{b}	35.5^{b}	33.9^{b}	33.9^{c}	33.5^{c}	65.4^{a}	68.5^{b}	67.7^{b}	69.1^{b}
Progressive Farmers' Practice	15.5^{b}	19.2^{b}	13.3^{b}	17.6^{b}	37.4^{ab}	35.9^{b}	35.4^{b}	35.1^{b}	66.7^{a}	70.5^{a}	69.2^{b}	70.4^{a}
ICM Practice	19.0^{a}	22.8^{a}	15.6^{a}	20.2^{a}	40.0^{a}	39.6^{a}	37.6^{a}	36.9^{a}	69.4^{a}	72.85^{a}	71.3^{a}	71.4^{a}
CD (p=0.05)	***	**	**	***	**	***	***	**	NS	***	**	***

Note: NS: Nonsignificant; * Significant at <0.05; ** Significant at <0.01; *** Significant at <0.001 (Statistical significance at 95%, 99%, and 99.9%, respectively that represents increasing levels of confidence that research results are not due to chance, corresponding to 5%, 1%, and 0.1% risks of false positives (p-values of 0.05, 0.01, 0.001). Higher confidence levels provide stronger evidence but result in wider confidence intervals, reducing precision. Superscript letters (a,b,c…) denotes statistical similarity (for same letter) and dissimilarity (different letters). Pl. refers to Plant.

Table 5: Yield and harvest indices of groundnut cultivars 'TG-37A' and 'KDG-128' as influenced by farming practices during Spring-Summer and Rainy (values represent pooled data of 2022 and 2023)

Treatment	Pod Yield (kg/ha)				Haulm Yield (kg/ha)				Total Yield (kg/ha)				Kernel Yield (kg/ha)				HI (%)			
	Spring-Summer		Rainy		Spring-Summer		Rainy		Spring-Summer		Rainy		Spring-Summer		Rainy		Spring-Summer		Rainy	
	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128
Farmers' Practice	2554^{c}	3177^{c}	1719^{a}	2432^{b}	3140^{c}	3875^{c}	3130^{b}	4276^{c}	5693^{c}	7052^{c}	4849^{c}	6708^{c}	1671^{b}	2179^{c}	1163^{b}	1676^{c}	44.9^{a}	45.5^{a}	35.9^{a}	37.4^{a}
Progressive Farmers' Practice	2808^{b}	3534^{b}	1870^{a}	2648^{b}	3448^{b}	4035^{a}	3347^{b}	4617^{b}	6256^{b}	7569^{b}	5217^{b}	7265^{b}	1880^{b}	2492^{b}	1293^{b}	1857^{b}	44.9^{a}	47.0^{a}	36.2^{a}	37.7^{a}
ICM Practice	3055^{a}	3774^{a}	2037^{a}	2911^{a}	3636^{a}	3639^{b}	3622^{a}	4974^{a}	6690^{a}	8413^{a}	5659^{a}	7886^{a}	2126^{a}	2748^{a}	1453^{a}	2071^{a}	45.6^{a}	44.9^{a}	36.4^{a}	38.1^{a}
CD (p=0.05)	**	***	NS	***	**	**	***	***	**	***	**	**	**	**	**	***	NS	NS	NS	NS

Note: NS: Nonsignificant; * Significant at <0.05; ** Significant at <0.01; *** Significant at <0.001 (Statistical significance at 95%, 99%, and 99.9%, respectively that represents increasing levels of confidence that research results are not due to chance, corresponding to 5%, 1%, and 0.1% risks of false positives (p-values of 0.05, 0.01, 0.001). Higher confidence levels provide stronger evidence but result in wider confidence intervals, reducing precision. Superscript letters (a,b,c…) denotes statistical similarity (for same letter) and dissimilarity (different letters).

Economics of cultivation

The economic attributes, including cost of cultivation, gross and net return, and benefit-cost ratio, were influenced significantly under different management practices during both the crop-growing seasons *viz.,* spring-summer and rainy seasons (Fig 4). The economic analysis of groundnut cultivation further revealed the clear superiority of ICM Practice over both Progressive and Farmers' Practices during both spring-summer and rainy seasons (Table 6). Cost of cultivation of groundnut cultivars 'TG-37A' and 'KDG-128' as influenced by management practices during spring-summer and rainy season is presented in Fig 4. Higher productivity under ICM resulted in significantly greater economic returns for both cultivars, with KDG-128 consistently outperforming TG-37A. During spring-summer, gross returns under ICM increased to ₹1,92,616 ha^{-1} in TG-37A (+19.3%) and ₹2,43,359 ha^{-1} in KDG-128 (+18.3%) compared to Farmers' Practice. Correspondingly, net returns were highest under ICM, reaching ₹1,40,296 ha^{-1} in TG-37A (+23.8%) and ₹1,89,766 ha^{-1} in KDG-128 (+21.4%). During the Rainy season, ICM Practice recorded gross returns of ₹1,40,348 ha^{-1} in TG-37A (+18.1%) and ₹1,97,366 ha^{-1} in KDG-128 (+19.1%), while net returns increased to ₹91,927 ha^{-1} (+23.5%) and ₹1,47,355 ha^{-1} (+23.1%), respectively, over Farmers' Practice. The benefit–cost ratio (BCR) was also highest under ICM Practice, improving from 3.35 to 3.68 in TG-37A and from 4.16 to 4.55 in KDG-128 during spring-summer, and from 2.67 to 2.90 and 3.61 to 3.95, respectively, during rainy, indicating superior economic viability of ICM-based groundnut production across the seasons and varieties (Table 6). The study showed that different economic parameters of groundnut crop cultivation were influenced by various management practices as it was apparent during both spring-summer and rainy seasons. Therefore, it was evident that the ICM Practice had an edge across the seasons and varieties compared to both Farmers' and Progressive Farmers' Practices.

Table 6: Economics of groundnut cultivars 'TG-37A' and 'KDG-128' as influenced by farming practices during Spring-Summer and Rainy (values represent pooled data of 2022 and 2023)

Treatment	Gross return (₹ ha^{-1})				Net return (₹ ha^{-1})				BCR			
	Spring-Summer		Rainy		Spring-Summer		Rainy		Spring-Summer		Rainy	
	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128	TG-37A	KDG-128
Farmers' Practice	161506^{c}	205745^{c}	118884^{b}	165746^{c}	113289^{c}	156257^{c}	74423^{b}	119695^{c}	3.35^{b}	4.16^{a}	2.67^{b}	3.61^{b}
Progressive Farmers' Practice	177457^{b}	227064^{b}	128968^{ab}	179886^{b}	126197^{b}	174531^{b}	81660^{b}	130988^{b}	3.47^{a}	4.32^{a}	2.73^{a}	3.68^{b}
ICM Practice	192616^{a}	243359^{a}	140348^{a}	197366^{a}	140296^{a}	189766^{a}	91927^{a}	147355^{a}	3.68^{a}	4.55^{a}	2.90^{a}	3.95^{a}
CD (p=0.05)	***	**	***	*	***	**	**	***	***	NS	*	***

Note: NS: Nonsignificant; * Significant at <0.05; ** Significant at <0.01; *** Significant at <0.001 (Statistical significance at 95%, 99%, and 99.9%, respectively that represents increasing levels of confidence that research results are not due to chance, corresponding to 5%, 1%, and 0.1% risks of false positives (p-values of 0.05, 0.01, 0.001). Higher confidence levels provide stronger evidence but result in wider confidence intervals, reducing precision. Superscript letters (a,b,c…) denotes statistical similarity (for same letter) and dissimilarity (different letters).

Quality parameters

The quality parameters of groundnut kernels, including moisture, oil, and protein content, were evaluated for TG-37A and KDG-128 under different farming practices during rainy 2023 (Table 7). It was apparent that most of the quality traits, genetically influenced by genotype concerned, were not varied under various management practices adopted during both the spring-summer and rainy seasons (Table 7). However, there were some exceptions to this in terms of scale. For example, kernel or seed moisture content was the highest under Farmers' Practice (6.68% for TG-37A and 5.94% for KDG-128), while ICM Practice recorded the highest oil content (49.0% for TG-37A and 54.4% for KDG-128). On the contrary, protein content was slightly higher in TG-37A but showed a slight reduction under ICM Practice compared to Farmers' Practice. However, statistical analysis indicated no significant differences across the practices. The improved oil content under ICM Practice is mainly attributed to optimized agronomic practices that enhance plant growth and oil synthesis and economic benefits of higher oil content in groundnuts intended for oil extraction. Despite a minor reduction in protein content, the increase in oil content makes ICM Practice more advantageous for maximizing oil yield. Thus, ICM practice had maintained an elevated oil content (and oil yield) thereby benefiting the profitability of the system under BMP.

Table 7: Groundnut quality parameters as influenced by farming practice and varieties (Rainy 2023)

Treatment	Kernel Moisture (%)		Oil content (%)		Protein content (%)	
	TG- 37A	KDG -128	TG- 37 A	KDG -128	TG -37A	KDG- 128
Farmers' Practice	6.68^{a}	5.94^{a}	47.6^{a}	52.9^{a}	31.3^{a}	25.9^{a}
Progressive Farmers' Practice	6.54^{a}	5.69^{a}	47.9^{a}	53.8^{a}	31.1^{a}	24.8^{a}
ICM Practice	6.59^{a}	5.90^{a}	49.0^{a}	54.4^{a}	30.0^{a}	24.1^{a}
CD (p=0.05)	NS	NS	NS	NS	NS	NS

Note: NS: Nonsignificant; Superscript letters (a,b,c…) denotes statistical similarity (for same letter) and dissimilarity (different letters).

Nutrient uptake

Nutrient uptake in respect of major nutrients (NPK) was significantly influenced by different management practices during both spring-summer and rainy seasons (Tables 8). It was observed that the nutrient uptake (NPK) in both the groundnut cultivars (TG-37A and KDG-128) was significantly higher under ICM Practice compared to progressive and conventional farmers' practices during both growing seasons, *viz.,* the spring-summer and rainy seasons (Table 8). Under ICM, nutrient uptake for TG-37A was approximately 150 kg/ha nitrogen, 16.6 kg/ha phosphorus, and 64.6 kg/ha potassium, while for KDG-128, the corresponding values were 149 kg/ha, 16.2 kg/ha, and 54.5 kg/ha, respectively. Similar trends were observed during the rainy season, with ICM consistently achieving the highest NPK uptake (Fig 5). Improved nutrient uptake under ICM Practice is mainly attributed to optimized agronomic parameters because of better management practices that enhance crop growth and NPK uptake with better profitability through higher oil content in groundnuts. Despite a negligible reduction in protein content of the kernel, the increase in oil content along with higher analysed nutrient content enable ICM Practice with the greater advantages following optimizing nutrient uptake. Thus, ICM practice had maintained at an elevated nutrient removed by the crop, thereby benefiting the robust performance of the crop under BMP. Similar pattern was followed during the second year (2023) too.

Table 8. Nutrient (NPK) uptake (kg/ha) by Groundnut cultivars as influenced by farming practices during Spring-Summer 2022 and Rainy 2022#

Treatment	Spring-Summer 2022						Rainy 2022					
	TG -37A			KDG -128			TG -37A			KDG -128		
	N	P	K	N	P	K	N	P	K	N	P	K
Farmers' Practice	109 ^{c}	12.5 ^{c}	40.6 ^{c}	115 ^{c}	12.0 ^{c}	44.4 ^{b}	111 ^{c}	13.7 ^{c}	41.1 ^{c}	114.1 ^{c}	12.8 ^{c}	42.3 ^{c}
Progressive Farmers' Practice	125 ^{b}	13.8 ^{b}	50.2 ^{b}	132 ^{b}	13.8 ^{b}	46.8 ^{b}	127 ^{b}	15.7 ^{b}	52.1 ^{b}	137.9 ^{b}	15.1 ^{b}	48.8 ^{b}
ICM Practice	150 ^{a}	16.6 ^{a}	64.6 ^{a}	149 ^{a}	16.2 ^{a}	54.5 ^{a}	149 ^{a}	18.5 ^{a}	64.0 ^{a}	160.1 ^{a}	17.4 ^{a}	55.9 ^{a}
CD (p=0.05)	***	***	**	***	***	**	***	***	***	**	**	***

Note: NS: Nonsignificant; * Significant at <0.05; ** Significant at <0.01; *** Significant at <0.001 (Statistical significance at 95%, 99%, and 99.9%, respectively that represents increasing levels of confidence that research results are not due to chance, corresponding to 5%, 1%, and 0.1% risks of false positives (p-values of 0.05, 0.01, 0.001). Higher confidence levels provide stronger evidence but result in wider confidence intervals, reducing precision. Superscript letters (a,b,c…) denotes statistical similarity (for same letter) and dissimilarity (different letters); #Similar pattern was followed during the second year (2023) too.

Discussion

Agriculture today is undergoing one of the most profound transformations in its history, standing at an intersection of food security, environmental sustainability, and emerging as well as disruptive technological innovations. Compounding this, declining per capita availability of arable land and fresh water, coupled with the escalating impacts of climate change, pose grave risks, with the International Panel on Climate Change (IPCC) warning that crop yields especially those of cereal could drop up to 25% under high-emission scenarios. These converging crises present a triple challenge for agriculture to produce more food (Scale or quantity), to produce better and more nutritious food (Quality of food), and to produce it more sustainably (stability in production aiming at growing more from less) without undermining the ecological foundations on which farming rely

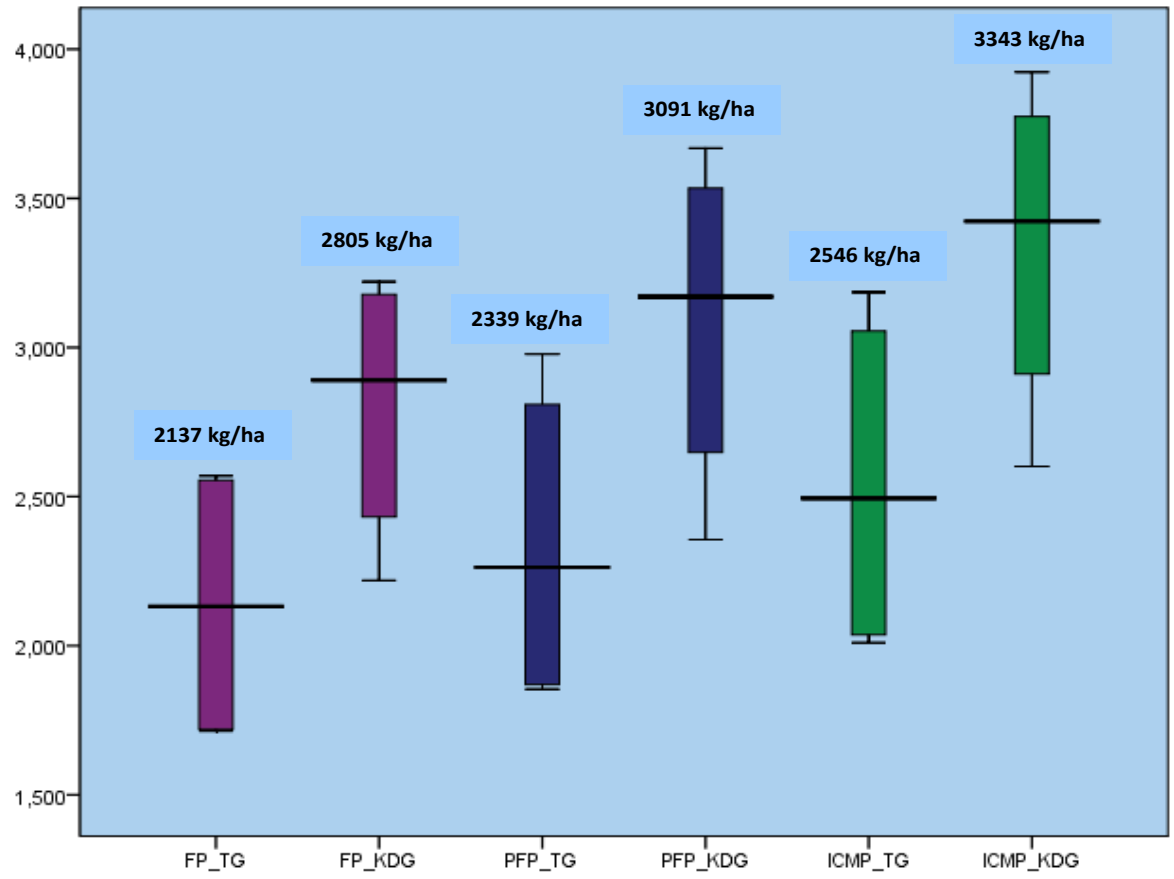
on. At the same time, the current 21st century is witnessing unprecedented transformations in how communities or systems live, work, and interact with natural and technological systems. Further, rapid advancements in science and technology are reshaping both livelihoods and resource use, ushering in the era of New Agricultural Niche. In this context, agriculture, the backbone of human civilization, must evolve not merely to feed the world but to nourish it, while preserving the economic and ecological balances. Therefore, it is essential to harmonize productivity, sustainability and equity in the agri-food systems of the future. In broad sense, it underlines the importance of integrating technologies for maximum benefits and advantages [2].

In this context, the role of integrated strategy or balancing approach is quite pertinent. The improved growth and development under ICM Practice can be attributed to the application of a Consortium of Plant Growth Promoting Rhizobacteria (PGPR 'NUTBOOST'), comprising *Pseudomonas gessardii* BHU1 (PGPR1), *Pseudomonas putida* S1(6) (PGPR2), and *Pseudomonas putida* BM6 (PGPR4). These microbes enhance plant growth by increasing ACC deaminase activity, which reduces stress ethylene levels, promoting better growth [19]. PGPR improve growth through nitrogen fixation, phosphate solubilization, and enhancing nutrient uptake, especially nitrogen, phosphorus, and potassium [20,21]. Their benefits include increased nutrient availability, improved root growth, and enhanced resistance to environmental stresses [22]. Additionally, PGPR secrete phytohormones like auxins, cytokinins, and gibberellins, further enhancing plant growth [23], and produce secondary metabolites that protect plants from phytopathogens. PGPR improve seed germination, early flowering, pod yield, biomass, and nutrient uptake[24]. The mechanisms of PGPR action are complex and influenced by soil properties, plant-microbe interactions, and environmental conditions [25]. Microbes interact with plants through root exudates, which attract beneficial microbes that convert nutrients into accessible forms, enhancing plant growth [26,27]). Recent studies further validate the positive impact of multi-strain PGPR consortia on crop performance. A 2025 field study in groundnut reported that microbial consortia combined with fertilizers significantly improved pod and haulm yield and economic returns [28]. Similarly, co-inoculation of PGPR with Rhizobium enhanced growth, nodulation, and nutrient mobilization under stress conditions [29]. Further, PGPR strains were shown to improve drought tolerance by increasing ACC deaminase activity, boosting antioxidant responses, and maintaining nutrient uptake [30]. These recent evidences also reinforce the effectiveness of PGPR consortia like NutBoost in improving nutrient use efficiency, productivity, and resilience in groundnut (based cropping) systems.

Average pod yield (kg/ha) of TG-37A and KDG-128 under different farming practices over the seasons of study (spring-summer 2022 to rainy 2023) is presented in Fig 3. ICM practice showed its superiority over other management practices because of more compatible and favourable need-based integration of matching technological innovations. Due to genotypic difference, KDG-128 again showed its yield advantages compared to TG-37A. This difference in yield either with management practice (ICM practice) or with KDG-128 is due to significant improvement in growth and yield attributes as evident in Table 3-5. As a result increase in yield to the extent of 207 and 252 kg/ha were evident or realized under ICM practice compared to progressive farmers' practice in respect of TG-37A and KDG-128, respectively. The overall (mean) productivity

performance for FP, PFP and ICMP were 2471, 2715 and 2945 kg/ha, respectively. Thus, an increase of 244 kg/ha (9.9%) through PFP over FP; and 230 kg/ha (8.5%) by through ICMP over PFP was evident. This was the cumulative effect of technological integration favoring in substantial yield increases following the improved practice (PFP and ICMP) [2]. Therefore, suitable amalgamation of technological innovation is the key to realization/success of productivity increases.

Fig 3: Average pod yield (Kg/ha) of TG37A and KDG128 under different farming years over the seasons of study (spring-summer 2022 to rainy 2023) FP: Farmers; practice, PFP: Progressive farmers' practice, ICP: Integrated Crop Management practice.

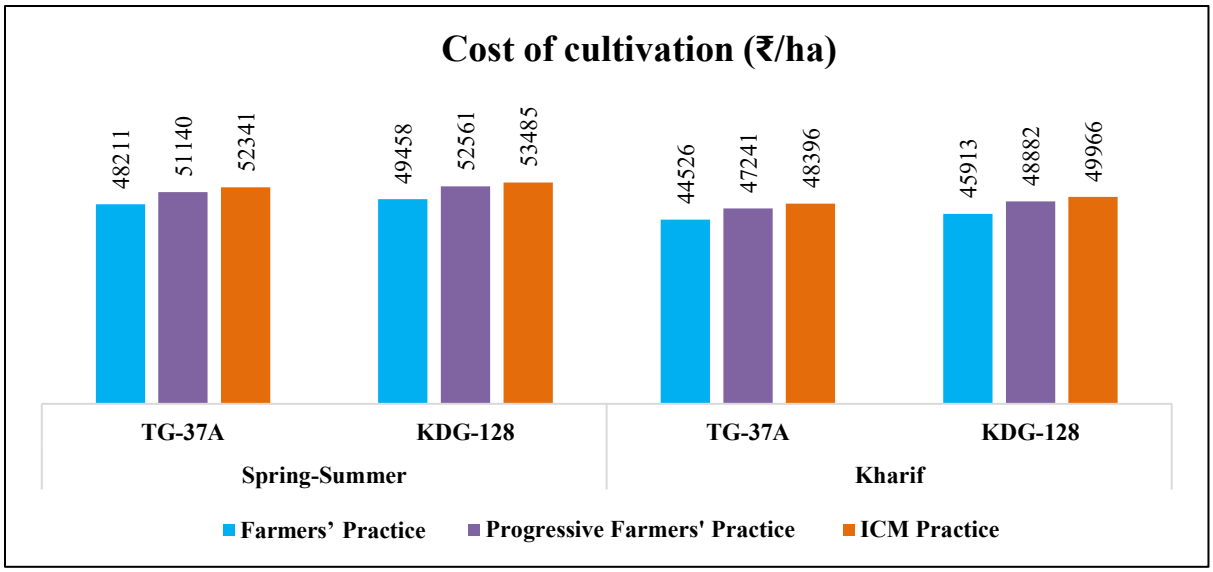


Further, the significant yield improvements under ICM Practice can be attributed to enhanced nutrient uptake (Table 8) and better plant health facilitated by plant growth promoting rhizobacteria (PGPR) and integrated nutrient management. PGPRs contribute to nitrogen fixation, phosphate solubilization, micronutrient availability, and phytohormone production, while also inducing systemic resistance against pests and pathogens [31,32]). They promote root and shoot growth, enhancing plant vigour and yield [33,34]). Integrated nutrient management, combined with biological interventions, has also been shown to substantially enhance yields [35,36]). The incorporation of gypsum and farmyard manure (FYM) in ICM further improves soil structure, moisture retention, and nutrient availability [37,38]). The combined application of PGPR, organic amendments, and optimized agronomic practices enhances biomass production, supporting higher pod and kernel

yields [39,40]). Recent studies further support the benefits of integrating PGPR with organic and inorganic nutrient sources. A peanut–wheat system study reported that combining RDF, FYM, and PGPR significantly improved pod yield, NPK uptake, and overall system productivity compared with fertilizer-only practices [41]. Under North-Gujarat conditions, reduced RDF combined with FYM/vermicompost and microbial inoculants enhanced kernel nutrient content and total NPK uptake in groundnut [42]. A recent review also highlighted that integrating organic amendments, biofertilizers, and chemical fertilizers consistently improves yield, soil health, and nutrient-use efficiency across crops [43]. These findings reinforce the effectiveness of integrated nutrient management with PGPR for achieving higher and more sustainable groundnut productivity. This integrated approach ensures sustained yield improvements, making ICM Practice a superior choice for achieving higher groundnut yields under both spring-summer and rainy conditions.

The consistently higher BCR under ICM (Table 6) indicates better returns on investment, confirming its financial viability for groundnut cultivation. Higher returns were also attributed to increased yield and cost efficiency under ICM[44]. The superior performance can be linked to higher biological and economic output without a proportional increase in production costs, enhancing profitability (Fig 4) as cost of cultivation plays a vital role in productivity acqisition. Additionally, the spring-summer season showed higher productivity and economic gains due to reduced environmental stresses. Therefore, integrating biological and chemical inputs ensures sustainable productivity and higher net returns, supporting the observed economic benefits of ICM Practice in groundnut cultivation[45].

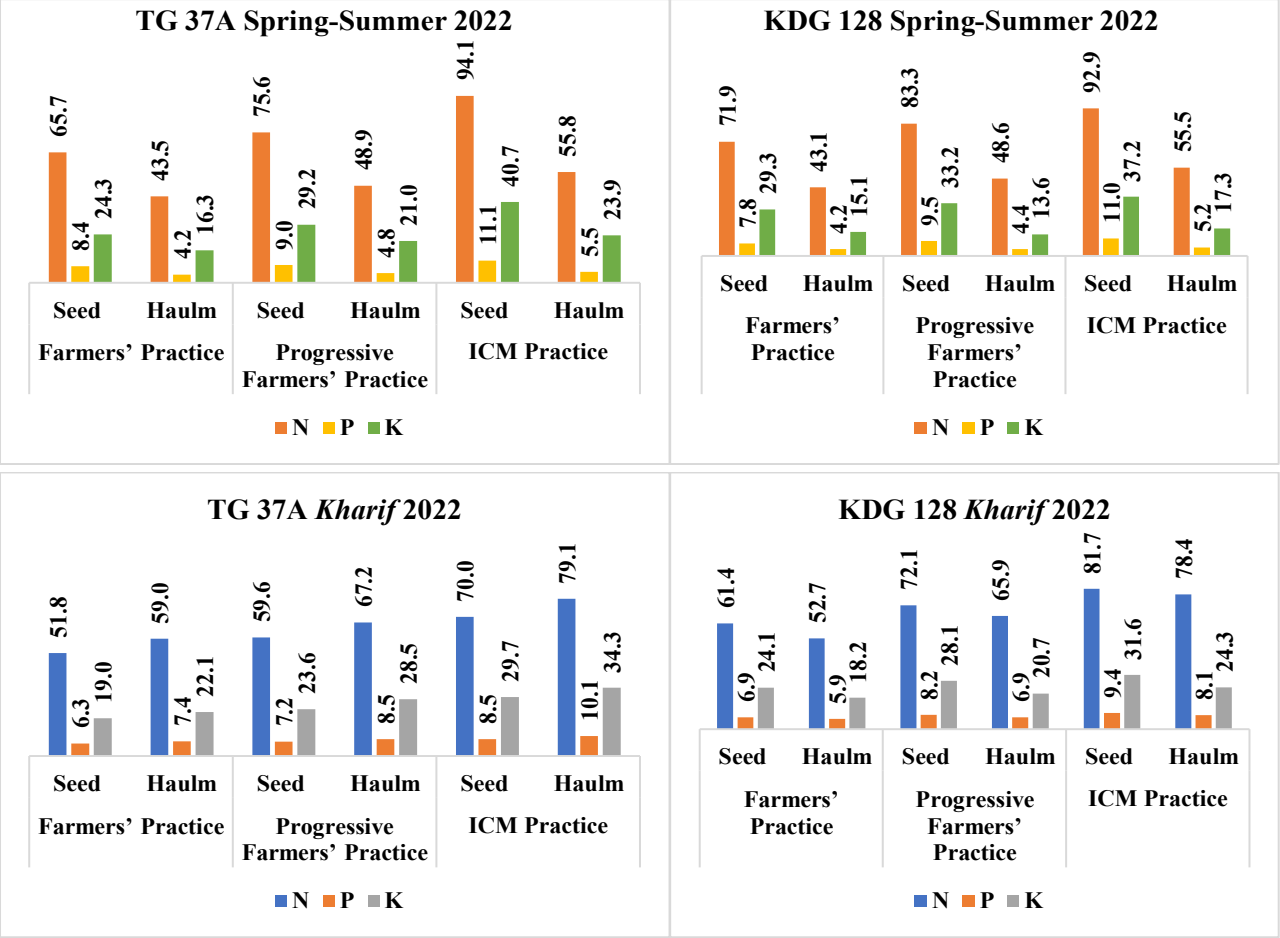
Fig 4: Cost of cultivation of groundnut cultivars 'TG-37A' and 'KDG-128' as influenced by farming practices during spring-summer and rainy (values represent pooled data of 2022 and 2023)



The importance of improved oil content under ICM Practice is further attributed to optimized agronomic practices that enhance plant growth and oil synthesis and economic benefits of higher oil content in groundnuts intended for oil extraction[46]. Despite a minor reduction in protein content, the increase in oil content makes ICM Practice more advantageous and sustainable for maximizing oil yield. And, the ICM practice had thus maintained an elevated oil content (and oil yield) thereby benefiting the profitability of the system under BMP.

The superior nutrient uptake under ICM (Table 8) can be attributed to the enhanced nutrient availability facilitated by PGPRs, which fix atmospheric nitrogen through nitrogenase enzymes and solubilize phosphate by producing organic acids, improving overall nutrient availability. PGPRs also aid in the biodegradation of FYM, contributing to nutrient release, while gypsum application further improves soil moisture content, enhancing nutrient uptake (Fig 5). PGPRs aid in improving nutrient availability and protecting against phytopathogens[47]. A synergistic effect of organic and inorganic sources enhances nutrient uptake through microbial activity in the rhizosphere [48,49]. Thus, Integrated Crop Management (ICM) practices are advantageous through significant increment in productivity and profitability in groundnut crop when compared to traditional or conventional farmers' practices and progressive farmers' methods. The ICM approach, that involves application of beneficial *Rhizobium* consortia, PGPR 'NutBoost', manure, nutrients/fertilizers, soil amendments (gypsum), and beneficial fungi (*Trichoderma viride)* working against soil-borne diseases, is thus handy for harvesting all the benefits from the soil-plant system. When this complements and supplements with economic benefits (higher net returns and favourable benefit-cost ratios) following the ICM practice, it leads in realization of higher and sustainable/profitable groundnut production [50]. Further, the environmental or ecosystem benefits of reducing fertilizer dosage via PGPR-NutBoost can't be ignored as it proves a boon for a holistic soil-crop management system through a viable alternative (for overall sustainability) in (groundnut) crop cultivation.

Fig 5: Nutrient uptake by seed and haulm of TG 37A and KDG 128 varieties under different farming practices in spring-summer 2022 and Rainy 2022.



Conclusion

The present study clearly demonstrated that implementing Integrated Crop Management (ICM) practices significantly enhanced groundnut yield and economic returns compared to conventional farmers' practices and progressive farmers' methods. The ICM approach, which included the application of *Rhizobium* consortia, PGPR 'NutBoost', farmyard manure, recommended NPK fertilizers, gypsum, and *Trichoderma viride*, consistently resulted in higher pod yields, improved shelling percentages, and increased seed indices for both TG- 37A and KDG- 128 cultivars across multiple seasons. Furthermore, economic analysis showed higher net returns and favourable benefit-cost ratios with the ICM practice, underscoring its effectiveness in achieving sustainable and profitable groundnut production. Moreover, the study highlighted the environmental/ecosystem benefits of reducing chemical fertilizer usage and suggested PGPR-NutBoost as a promising alternative for sustainable soil management and crop productivity enhancement in groundnut cultivation. Given the consistency of outcomes across two seasons, two years and two varietal (habit) groups, the study indicated strong potential for replicability of the ICM approach in similar agro-climatic conditions for achieving broader system-level benefits in groundnut-based cropping systems.

Limitations

1. The presented study has been conducted in Junagadh, Gujarat which represents specific soil and agro-climatic conditions. Thus, multi-location validation of the study is needed for making recommendations at national level. However, similar trials are conducted at different sites of the country which confirmed the finding with certain modifications in the input-supply system due to site- specific nature.
2. The study has been done involving two cultivars, one each form Spanish and Virginia habit group. As varietal response to agronomic interventions may vary with specific genotype(s), the results may not be same for the all the varieties belonging to a particular habit group.
3. As mentioned, the study has been done over two years and across season of the year (spring-summer and rainy seasons). However, environment conditions may further influence the type and scale of different parameters of study and its long-term effects so far its assessment on dynamics of soil fertility and crop productivity, production economics, ecology of microbes, nutrient-use efficiency and sustainability of the production system are concerned.
4. The components of ICM package are evaluated collectively (and not in isolation), the distinguished quantification of the individual contribution and relative efficiency of each intervention may not be separated within the experimental results noted.

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Author Contributions

Conceptualization, Methodology, Statistical Analysis, CS Praharaj, Kiran Reddy; Investigation, CS Praharaj, Aaradhana Chilwal, Keval Hirapara and Kiran Reddy; Data Curation and Approval by Institute, CS Praharaj; Supervision, Writing-Draft, CS Praharaj, Aaradhana Chilwal, Keval Hirapara; Writing- Review and editing, CS Praharaj, Aaradhana Chilwal, Keval Hirapara and Kiran Reddy.

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Declarations

Competing interest

The authors declare no competing interests.

Data Availability Statement

The data supporting the findings of this study are included within the article and additional data are available from the corresponding author upon reasonable request to CS Praharaj.

REFERENCES

1. Gregory, P. J., Ingram, J. S. I., Andersson, R., Betts, R. A. & Brovkin, V. Environmental consequences of alternative practices for intensifying crop production. *Agric. Ecosyst. Environ.* **88**, 279–290 (2002).

2. Praharaj, C. S., Singh, U., Singh, S. S. & Kumar, N. Tactical water management in field crops: The key to resource conservation. *Curr. Sci.* **115**, 1262–1269 (2018).

3. Heba, M. N., Rana, D. S., Choudhary, A. K., Dass, A., Rajanna, G. A. & Pande, P. Improving productivity, quality and biofortification in groundnut (*Arachis hypogaea* L.) through sulphur and zinc nutrition in alluvial soils of the semi-arid region of India. *J. Plant Nutr.* **44**, 1151–1174 (2021).

4. Meena, H. N., Ajay, B. C., Rajanna, G. A., Yadav, R. S., Jain, N. K. & Meena, M. S. Polythene mulch and potassium application enhances peanut productivity and biochemical traits under sustained salinity stress condition. *Agric. Water Manag.* **273**, 107903 (2022).

5. DAFW. *Agricultural Statistics of India 2022–23* (Publication No. ASI-2023). Department of Agriculture and Farmers Welfare, Government of India (2023).

6. Gopinath, K. A., Rajanna, G. A., Venkatesh, G., Jayalakshmi, M., Kumari, V. V., Prabhakar, M., Rajkumar, B., Chary, G. R. & Singh, V. K. Influence of crops and different production systems on soil carbon fractions and carbon sequestration in rainfed areas of semi-arid tropics in India. *Sustainability* **14**, 4207 (2022).

7. Sarkar, R. K., Karmakar, S. & Chakraborty, A. Response of summer green gram (*Phaseolus radiatus*) to nitrogen, phosphorus application and bacterial inoculation. *Indian J. Agron.* **38**, 578–581 (1997).

8. Veeramani, P., Subrahmaniyan, K. & Ganesaraja, V. Organic manure management on groundnut: A review. *Wudpecker J. Agric. Res.* **1**, 238–243 (2012).

9. Singh, A. L. Mineral nutrient requirement, their disorders and remedies in groundnut. In: *Groundnut Research in India*, 137–159 (2004).

10. Soil Survey Staff. *Keys to Soil Taxonomy*, 12th edn. USDA-NRCS (2014).

11. Jackson, M. L. *Soil Chemical Analysis*. Prentice Hall of India Pvt. Ltd. (1973).

12. Walkley, A. & Black, I. A. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.* **37**, 29–38 (1934).

13. Subbiah, B. V. & Asija, G. L. A rapid procedure for the estimation of available nitrogen in soils. *Curr. Sci.* **25**, 259–260 (1956).

14. Olsen, S. R., Cole, C. V., Watanabe, F. S. & Dean, L. A. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *USDA Circular* **939** (1954).

15. Blake, G. R. & Hartge, K. H. Bulk density. In: *Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods*, 363–375 (1986).

16. Richards, L. A. Pressure-membrane apparatus—construction and use. *Agric. Eng.* **28**, 451–454 (1947).

17. Gomez, K. A. & Gomez, A. A. *Statistical Procedures for Agricultural Research*. John Wiley & Sons, New York, NY (1984).

18. IBM Corp. *IBM SPSS Statistics for Windows*, Version 24.0. IBM Corp., Armonk, NY (2016).

19. El Husseini, M., Helmut, B. & Helmut, J. The biofertilising effect of seed dressing with PGPR *Bacillus amyloliquefaciens* FZB 42 combined with two levels of mineral fertilizing in African cotton production. *Arch. Phytopathol. Plant Prot.* **45**, 2261–2271 (2012).

20. Santoyo, G., Moreno-Hagelsieb, G., del Carmen Orozco-Mosqueda, M. & Glick, B. R. Plant growth-promoting bacterial endophytes. *Microbiol. Res.* **183**, 92–99 (2016).

21. Gouda, S., Kerry, R. G., Das, G., Paramithiotis, S., Shin, H. S. & Patra, J. K. Revitalization of plant growth promoting rhizobacteria for sustainable development in agriculture. *Microbiol. Res.* **206**, 131–140 (2018).

22. Vessey, J. K. Plant growth promoting rhizobacteria as biofertilizers. *Plant Soil* **255**, 571–586 (2003).

23. Timmusk, S., Behers, L., Muthoni, J., Muraya, A. & Aronsson, A. C. Perspectives and challenges of microbial application for crop improvement. *Front. Plant Sci.* **8**, 49 (2017).

24. Khan, N., Bano, A. M. & Babar, A. Impacts of plant growth promoters and plant growth regulators on rainfed agriculture. *PLoS One* **15**, e0231426 (2020).

25. Gamalero, E., Berta, G., Massa, N., Glick, B. R. & Lingua, G. Interactions between *Pseudomonas putida* UW4 and *Gigaspora rosea* BEG9 and their consequences on the growth of cucumber under salt stress conditions. *J. Appl. Microbiol.* **108**, 236–245 (2010).

26. Ahemad, M. & Kibret, M. Mechanisms and applications of plant growth promoting rhizobacteria: Current perspective. *J. King Saud Univ. Sci.* **26**, 1–20 (2014).

27. Vejan, P., Abdullah, R., Khadiran, T., Ismail, S. & Nasrulhaq Boyce, A. Role of plant growth promoting rhizobacteria in agricultural sustainability—A review. *Molecules* **21**, 573 (2016).

28. Jyothi, V., Vijayalakshmi, D., Prabhakar Reddy, T. & Sridhar, K. Effect of microbial consortia on yield and economics of groundnut in Alfisols. *Int. J. Res. Agron.* **8**, 306–310 (2025).

29. Sankareswari, R. U., Sivasankari Devi, T. & Prabhaharan, J. Coinoculation effect of endophytic PGPR and *Rhizobium* for pigeonpea yield performance. *Int. J. Agric. Food Sci.* **7**, 240–242 (2025).

30. Kesavardhini, K., Essa, I. M., Nayak, A. K. *et al.* Harnessing plant growth promoting rhizobacteria to bolster drought tolerance in plants. *Discov. Appl. Sci.* (2025).

31. Novo, L. A. B., Castro, P. M. L., Alvarenga, P. & Silva, E. F. Plant growth-promoting rhizobacteria-assisted phytoremediation of mine soils. In: *Bio-Geotechnologies for Mine Site Rehabilitation*, 281–295 (2018).

32. Pathania, P., Rajta, A., Singh, P. C. & Bhatia, R. Role of plant growth-promoting bacteria in sustainable agriculture. *Biocatal. Agric. Biotechnol.* **30**, 101842 (2020).

33. Vacheron, J., Desbrosses, G. & Bouffaud, M. L. Plant growth-promoting rhizobacteria and root system functioning. *Front. Plant Sci.* **4**, 356 (2013).

34. Nascimento, F. X., Rossi, M. J., Glick, B. R. & Rossi, M. J. Indole-3-acetic acid biosynthesis by *Burkholderia* sp. in cowpea (*Vigna unguiculata* L. Walp.). *Microorganisms* **7**, 172 (2019).

35. Sharma, M. P., Jastrow, J. D. & Klironomos, J. N. Soil microbial communities and their potential role in soil carbon dynamics under global change: A review. *Soil Biol. Biochem.* **33**, 875–885 (2016).

36. Tilak, K. V. B. R., Ranganayaki, N. & Pal, K. K. Growth and yield response of crops to plant growth promoting rhizobacteria. In: *Plant Microbes Symbiosis: Applied Facets*, Springer, New Delhi, 45–62 (2017).

37. Chen, Y., Liu, Q. & Gao, Y. Influence of gypsum application on alleviating aluminum toxicity in acid soils. *J. Environ. Sci.* **68**, 269–277 (2018).

38. Venkateswarlu, B., Srinivasa Rao, C. & Ramana, D. B. V. Nutrient management in rainfed drylands: Challenges and opportunities. *Indian J. Fertil.* **13**, 18–31 (2017).

39. Kumar, A., Singh, R. & Yadav, A. N. Microbial diversity and biofertilizers: Current research and future perspective. *Microbiol. Res.* **242**, 126667 (2021).

40. Yadav, A. N., Verma, P. & Singh, B. Plant growth promoting microbial consortia for sustainable agriculture: Current status and future prospects. *Indian J. Microbiol.* **60**, 174–188 (2020).

41. Jat, R. A., Jain, N. K., Yadav, R. S., Reddy, K. K., Choudhary, R. R., Zala, P. V., Meena, H. N., Sarkar, S., Rathore, S. S., Sharma, G. K., Kumawat, A., Jinger, D. & Jha, P. K. System-based integrated nutrient management improves productivity, profitability, energy use efficiency and soil quality in peanut–wheat cropping sequence in light black soils. *Sustainability* **15**, 1361 (2023).

42. Patel, K. K., Patel, J. M., Patel, J. A., Chauhan, K. J. & Patel, R. M. Optimizing nutrient content and uptake in groundnut through integrated nutrient management under North Gujarat conditions. *Int. J. Adv. Biochem. Res.* **8**, 612–616 (2024).

43. Ghosh, A., Bharatbhushan, M., Kumaravel, S., Imade, S. R., Upadhyay, S. P., Borah, P., Sinha, S. K., Maraskolhe, M., Swain, S. K. & Singh, G. Integrated soil fertility management: Combining organic and inorganic inputs for better yield. *Int. J. Res. Agron.* **8**, 100–109 (2025).

44. Chandrasekaran, B., Annadurai, K. & Somasundaram, E. *A Textbook of Agronomy*. New Age International (2010).

45. Singh, J. S., Pandey, V. C. & Singh, D. P. Efficient soil microorganisms: A new dimension for sustainable agriculture and environmental development. *Agric. Ecosyst. Environ.* **140**, 339–355 (2019).

46. Patil, D. R., Naik, R. M. & Ganapathy, K. N. Integrated crop management practices for enhancing productivity and quality of groundnut. *J. Oilseeds Res.* **27**, 123–126 (2010).

47. Kumar, A., Maurya, B. R., Raghuwanshi, R., Meena, V. S. & Islam, M. T. Co-inoculation with *Enterobacter* and Rhizobacteria on yield and nutrient uptake by wheat (*Triticum aestivum* L.) in the alluvial soil under Indo Gangetic Plain of India. *J. Plant Growth Regul.* **36**, 608–617 (2017).

48. Hakim, S., Naqqash, T., Nawaz, M. S., Laraib, I., Siddique, M. J., Zia, R., Mirza,M. S. & Imran, A. Rhizosphere engineering with plant growth-promoting microorganisms for agriculture and ecological sustainability. *Front. Sustain. Food Syst.* **5**, 617157 (2021).

49. Kabiraj, A., Majhi, K., Halder, H., Let, M. & Bandopadhyay, R. Role of plant growth-promoting rhizobacteria (PGPR) for crop stress management. In: *Sustainable Agriculture in the Era of Climate Change*, Springer, Cham, Switzerland, 367–389 (2020).

50. Praharaj, C. S., Reddy, Kiran, Chilwal, Aaradhana & Hirapara, Keval. Equating low-cost natural farming vis-à-vis integrated crop management and organic practices in groundnut-wheat cropping system in Gujarat Plains of India. *Intern. J. Plant Prod*. **19,** 219-238 (2025).