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RESEARCH ARTICLE

Strategic application of nano sulphur and nano calcium for groundnut growth and yield response: A multivariate approach

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Abstract

Groundnut (*Arachis hypogaea* L.) is a significant oilseed crop widely cultivated for its high oil content and nutritional value. To meet the increasing demand for better oil yield and quality, improving productivity through effective nutrient management is crucial. Hence, the field study was conducted at Tamil Nadu Agricultural University to evaluate the effects of foliar applications of nano sulphur and nano-calcium on the growth and yield of groundnut. The experiment involved fifteen treatments with different concentrations and application timings of nano sulphur and nano calcium sprays, evaluated using a Randomised Block Design (RBD). The findings showed that the combined application of nano sulphur at 200 ppm at 30 and 45 Days After Sowing (DAS) (T_6) significantly boosted dry matter production, SPAD readings and pod development. T_6 also achieved the highest pod yield (2468 kg ha^{-1}), seed yield (1701 kg ha^{-1}), oil yield (820.7 kg ha^{-1}) and oil content (48.27 %), performing comparably to T_5 (nano sulphur 100 ppm at 30 & 45 DAS) and T_{13} (recommended NPK + gypsum). The untreated control (T_{15}) recorded the lowest yields. Correlation and regression analyses demonstrated a strong positive correlation between the total number of pegs and all major yield attributes. The study concludes that nano sulphur at 200 ppm can significantly enhance productivity and oil quality in groundnuts, providing a sustainable alternative to traditional fertilization methods.

Keywords: foliar spray; groundnut; nano calcium; nano sulphur

Introduction

Agriculture is the backbone of many developing nations and supports over 60 % of the population. However, modern agriculture faces serious constraints, such as nutrient depletion, climate variability, water scarcity, declining soil health and stagnating crop yields. These challenges necessitate sustainable innovations, such as nanotechnology, to improve crop productivity and resource use efficiency (1).

Nanotechnology deals with materials at the nanoscale (1-100 nm), offering enhanced reactivity, targeted delivery and reduced environmental impact. In India, ICAR promotes nanotechnology to address nutrient deficiencies, pest management and soil health through precision agriculture (2). Both top-down and bottom-up synthesis methods are employed in developing nanomaterials, depending on whether the process involves reducing bulk materials to the nanoscale or assembling structures atom-by-atom. These techniques enable the integration of nutrients into nanosized carriers, thereby facilitating the production of nano fertilizers. Furthermore, surface modification during this process can convert cationic nutrients into more bioavailable anionic forms, improve nutrient delivery efficiency and plant uptake and enhance physiological functions (3).

Groundnut (*Arachis hypogaea* L.), a protein- and oil-rich legume, is widely cultivated in India, ranking second in global production. Groundnut is cultivated in approximately 120 countries, covering approximately 30.92 million hectares globally, yielding an annual production of 54.3 million tonnes. Asia accounts for the majority share (59.5 %) of this output, with China and India being the foremost contributors, producing 19.27 million tonnes and 10.29 million tonnes respectively as of 2023. Within India, Gujarat leads national production with 3.674 million tonnes, followed by Rajasthan (2.086 million tonnes), Madhya Pradesh (0.909 million tonnes), Tamil Nadu (0.7 million tonnes) and Karnataka (0.369 million tonnes) (4).

Groundnut kernels are a valuable source of protein and edible oil, accounting for approximately 50 % of the total. The remaining seed portion is enriched in essential nutrients, including high-quality proteins (21.4-26.45 %), carbohydrates (ranging from

6 to 24.9 %) and vitamins such as E and C. The extracted oil is predominantly unsaturated fatty acids (approximately 80 %), with the remainder being saturated fats (20 %), making it suitable for various uses, including culinary applications, Vanaspati manufacturing, soap production and cosmetic products such as cold creams (5). Despite its nutritional and economic value, its yield is often limited by calcium (Ca) and sulphur (S) deficiencies, especially in the coarse-textured soils of Tamil Nadu, which negatively impacts plant development, yield potential and seed quality (6).

Sulphur has emerged as the fourth essential nutrient for plant growth, gaining recognition after being historically underestimated because of its naturally adequate inputs. However, shifts in agricultural practices have led to widespread sulphur deficiencies, which adversely affect soil fertility and crop productivity. Ensuring sufficient sulphur availability is vital for improving the crop yield, protein synthesis and oil quality. Various sulphur-based amendments, including elemental sulphur, gypsum, phosphogypsum and pyrite, can effectively supply sulphur to oilseed crops such as groundnut, with a recommended application rate of 30-40 kg S/ha. While plants predominantly absorb sulphur in the form of sulphate (SO_4^{2-}), they can also utilize thiosulfate ($S_2O_3^{2-}$) and to a lesser extent, sulphur dioxide (SO_2) absorbed through foliar surfaces (7). Sulphur plays a key role in amino acid synthesis, enzyme function and oil formation, whereas calcium is critical for pod filling, cell wall development and reproductive success (8).

Calcium plays a critical role in the reproductive phase of groundnuts, with its requirement peaking during the pod-filling stage compared to flowering. Approximately 90 % of the absorbed calcium was directed toward the pods between 20- and 80-days following peg penetration. However, owing to limited uptake through the roots, calcium transport to developing pods is often delayed. Optimal calcium availability occurs in soils with a pH between 7 and 8; under more acidic conditions, calcium becomes less accessible, necessitating external supplementation to ensure adequate uptake (9).

As calcium is a relatively immobile nutrient within plants, it primarily moves to newly formed tissues and cannot be relocated once assimilated. This immobility underscores the importance of its continuous presence in the soil for sustained plant growth. Although soil-based calcium applications contribute to both yield improvement and better soil properties, foliar sprays are generally more efficient in rapidly addressing calcium deficiencies (10).

Although gypsum is a conventional source of Ca and S, it poses practical challenges, such as bulkiness, nutrient leaching and slow release (11). Nano formulations can overcome these issues through reduced dosage, efficient absorption and targeted delivery. Foliar sprays of nano calcium at 30 and 45 DAS have improved nutrient uptake, enhanced photosynthesis and increased groundnut pod and seed yields (12).

Therefore, integrating nano fertilizers in foliar nutrient management represents a promising strategy for improving oilseed crop performance and ensuring sustainable agricultural intensification in nutrient-depleted environments.

Materials and Methods

Sulphur nanoparticle synthesis

A reaction mixture was prepared by combining 50 mL of 1 M sodium thiosulfate pentahydrate ($Na_2S_2O_3·5H_2O$) with 30 mL of 0.93 mM CTAB at room temperature. The solution was mechanically stirred at 120 rpm and maintained at 40 °C in a constant-temperature water bath. Subsequently, 100 mL of 2 M hydrochloric acid (HCl) was added dropwise under continuous stirring. After approximately 40 min, the formation of a yellow precipitate indicated the completion of the reaction. The resulting precipitate was collected immediately, thoroughly washed with distilled water and dried for further use (13).

Calcium nanoparticle synthesis

Nano calcium oxide (CaO) was synthesized using sodium hydroxide (NaOH) and calcium chloride dihydrate ($CaCl_2·2H_2O$) as precursor materials. Separate aqueous solutions of 1 M $CaCl_2·2H_2O$ (20 mL) and 2 M NaOH (20 mL) were prepared and heated to 80 °C to ensure complete dissolution and uniformity. The NaOH solution was then added dropwise to the $CaCl_2·2H_2O$ solution for 30 min under constant stirring at 1300 rpm. This reaction resulted in the formation of a white precipitate. This precipitate was washed thoroughly and then calcined at 650 °C for 1 hr to obtain nano-sized calcium oxide particles (14).

Experimental details

Field experiments were conducted at the Department of Agronomy, Tamil Nadu Agricultural University (TNAU), Coimbatore, to evaluate the effect of foliar application of nano sulphur and nano calcium on the growth and yield of groundnut (*Arachis hypogaea* L.). The variety used for this study was VRI 10, a popular cultivar known for its suitability under irrigated conditions. The experiment was laid out in a RBD with 15 treatments and three replications. The treatments included foliar sprays of nano sulphur and nano calcium at varying concentrations and application timings, recommended nutrient practices and an untreated control. The treatment details are as follows in Table 1.

The crop was sown at a spacing of 30 × 10 cm. Uniform cultural and irrigation practices were followed across all treatments as per the TNAU recommendations to ensure proper crop growth. Foliar sprays were applied using a handheld knapsack sprayer during the morning hours to ensure uniform

Table 1. Treatment details of the experiment

Treatments	Treatments details
T_1	Foliar spray of nano sulphur 100 ppm at 30 DAS
T_2	Foliar spray of nano sulphur 200 ppm at 30 DAS
T_3	Foliar spray of nano sulphur 100 ppm at 45 DAS
T_4	Foliar spray of nano sulphur 200 ppm at 45 DAS
T_5	Foliar spray of nano sulphur 100 ppm at 30 & 45 DAS
T_6	Foliar spray of nano sulphur 200 ppm at 30 & 45 DAS
T_7	Foliar spray of nano calcium 100 ppm at 30 DAS
T_8	Foliar spray of nano calcium 200 ppm at 30 DAS
T_9	Foliar spray of nano calcium 100 ppm at 45 DAS
T_{10}	Foliar spray of nano calcium 200 ppm at 45 DAS
T_{11}	Foliar spray of nano calcium 100 ppm at 30 & 45 DAS
T_{12}	Foliar spray of nano calcium 200 ppm at 30 & 45 DAS
T_{13}	Recommended dose of NPK + Gypsum
T_{14}	Recommended dose of NPK alone
T_{15}	Absolute control

coverage. The recommended dose of fertilizer for groundnut (25:50:75 kg NPK ha^{-1}) was applied as the base for the relevant treatments. In T_{13}, gypsum was applied at 400 kg ha^{-1} as per standard practice to enhance calcium and sulphur availability. Nano sulphur and nano calcium solutions were prepared freshly before application by diluting the respective nano formulations to the required concentrations of 100 ppm and 200 ppm. Foliar sprays were carried out 30 DAS and/or 45 DAS as per the treatment schedule.

Observations were recorded on growth parameters (dry matter production, SPAD), yield attributes (total number of pegs, total number of pods, number of pop seeds, total number of mature pods, peg pod conversion ratio, shelling percentage), pod, seed yield, haulm yield, oil percentage and oil yield.

Peg pod conversion ratio

The peg-pod conversion ratio was calculated using the following equation:

$$\text{Peg pod conversion ratio} = \frac{\text{Total number of pods}}{\text{Total number of pegs}} \times 100$$

Shelling percentage (%)

The shelling percentage was calculated using the following formula:

$$\text{Shelling percentage} = \frac{\text{Weight of shelled kernels}}{\text{Weight of unshelled pods}} \times 100$$

Oil yield (kg ha^{-1})

The oil yield was calculated using the following formula:

$$\text{Oil yield (kg ha}^{-1}\text{)} = \frac{\text{Oil content (\%)}}{100} \times \text{Kernel yield (kg ha}^{-1}\text{)}$$

Statistical analysis

The previously described methodology was used to analyze the data from the field experiments (15). The F-test and 5 % critical differences were used to determine significance. R software was used for statistical analysis and data visualization, which significantly supported the research process.

Results and Discussion

Dry Matter Production (DMP)

The heat map analysis of DMP exhibited considerable variation among treatments across all growth stages (30 DAS, 60 DAS and harvest) (Fig. 1). At 30 DAS, the highest DMP was recorded in T_{10} and T_3 (both 475.2 kg ha^{-1}), followed by T_8 (469.2 kg ha^{-1}). In contrast, T_{15} had the lowest DMP at this stage (298.3 kg ha^{-1}), which was significantly lower than that of the other treatments.

At 60 DAS, T_6 produced the highest DMP (4166 kg ha^{-1}), followed by T_5 (4134 kg ha^{-1}) and T_{13} (4118 kg ha^{-1}), all of which were significantly higher than the lowest DMP in T_{15} (2904 kg ha^{-1}). Several treatments, including T_1, T_2, T_3 and T_{10}, were statistically significant, with values ranging between 3864 and 3953 kg ha^{-1}. At harvest, the highest DMP was observed at T_{13} (7429 kg ha^{-1}), which was statistically equivalent to T_6 (7417 kg ha^{-1}) and T_5(7330 kg ha^{-1}). In contrast, the lowest DMP was recorded in T_{15} (4336 kg ha^{-1}). Sulphur significantly contributes to improved crop growth by enhancing cell division, cell enlargement and elongation, thereby facilitating uniform vegetative development (16). It also promotes the biosynthesis of chlorophyll as it forms part of the succinyl-CoA molecule, which is crucial in this process. This ultimately leads to an increase in photosynthate production and a greater dry matter accumulation. Additionally, sulphur improves the availability and uptake of macro- and micronutrients and enhances soil

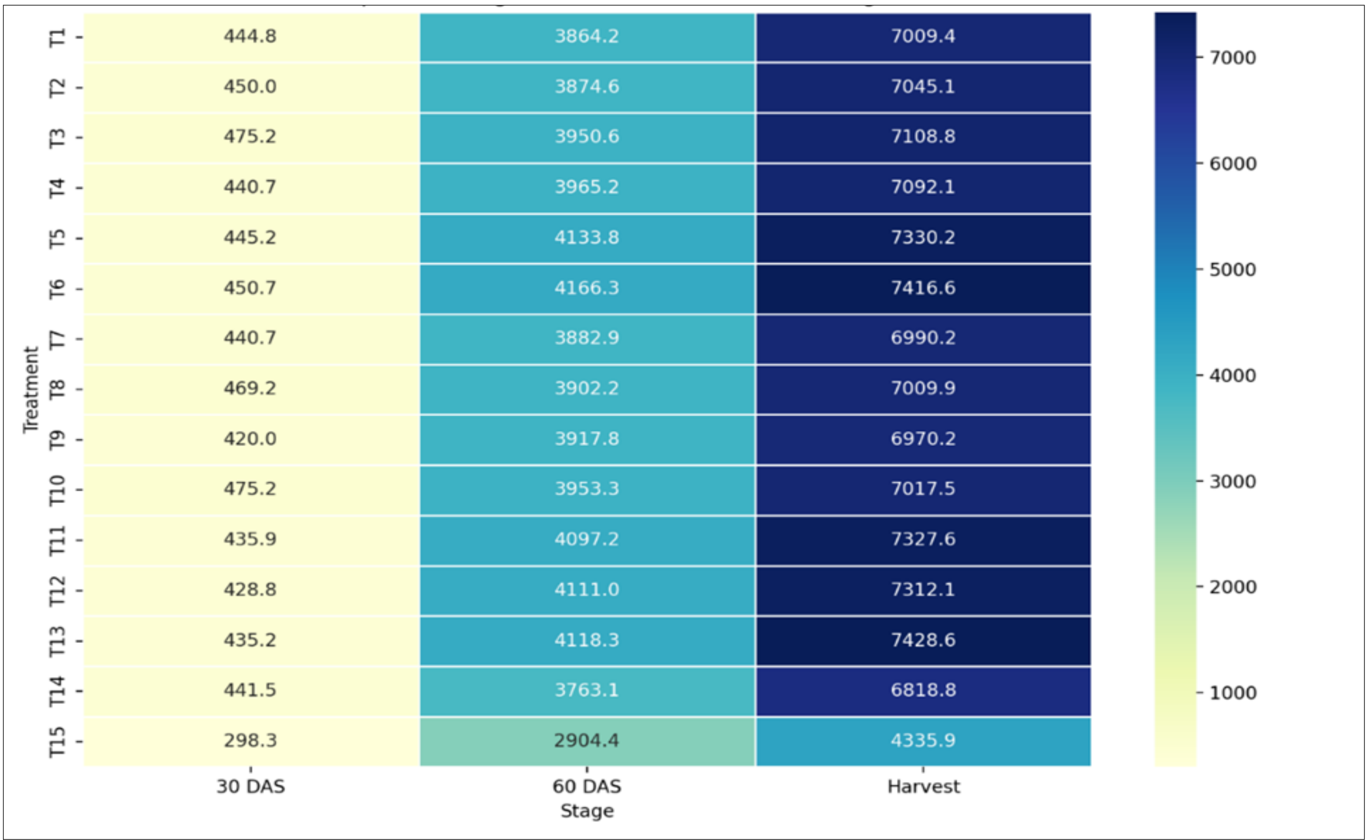

Fig. 1. Heat map analysis of across treatments on DMP (kg ha^{-1}) at different growth stages in groundnut.

conditions, further supporting efficient nutrient and water use (17), these findings are consistent with those reported previously (18, 19).

SPAD readings

At 30 DAS, the highest SPAD value was recorded at T_{14} (33.20), which was statistically like that at T_{12} (33.12) and T_{11}/T_{10} (both 32.92) (Fig. 2). The lowest SPAD value at this stage was observed in T_{15} (26.85). At 60 DAS, the highest reading was observed in T_6 (40.94), followed by T_5 (40.11) and T_{13} (39.75), the lowest value was recorded in T_{15} (30.97). T_4 also showed a notably high reading (39.87), which was statistically comparable to of that the best treatments. At harvest, T_6 recorded the highest SPAD reading (34.30), followed by T_{13} (34.00) and T_5 (33.88). The lowest reading at harvest was observed in T_{15} (25.11). The role of sulphur in enhancing chlorophyll content is well documented, primarily because of its involvement in the biosynthesis of essential molecules and its influence on nutrient uptake. As a constituent of amino acids and enzymes, sulphur indirectly supports the development and maintenance of chloroplasts, thereby elevating the SPAD values and improving photosynthetic capacity. Nano-sulphur, in particular, has been shown to increase the efficiency of chloroplasts and photosynthetic enzymes, directly impacting chlorophyll accumulation and SPAD readings (20).

Yield attributes

The peg and pod attributes of groundnuts exhibited significant variation among the treatments (Table 2). The highest number of pegs was recorded in T_6 (37.88), followed by T_5 (36.76) and T_{13} (36.25), while the lowest number was observed in T_{15} (24.25). Similarly, T_6 also produced the maximum total number of pods (27.58), followed by T_5 (26.61) and T_{13} (26.10), showing comparable results. In contrast, T_{15} had the lowest pod number (15.50). Sulphur plays a pivotal role in protein and vitamin synthesis, both of which are essential for enhancing the grain yield. Regarding mature pod formation, T_{13} exhibited the highest number of mature pods (24.85), followed closely by T_6 (24.39), T_5 (23.61) and T_{15} recorded the lowest (10.46). The peg-to-pod conversion ratio was highest in T_6 (72.85 %), followed by T_{13} (72.08 %) and T_5 (70.57 %), indicating greater efficiency in pod development from pegs. Conversely, T_{15} had the lowest conversion ratio (63.92 %), reflecting reduced reproductive efficiency. These results collectively demonstrate that treatments T_5, T_6 and T_{13} were most effective in enhancing peg and pod development traits, which likely contributed to their superior yield performance. One fundamental process is the sulphur-induced synthesis of methionine, a biological precursor of ethylene that influences plant development (21). Additionally, sulphur application has been associated with an increased number of pods per plant, likely due to an expansion in the photosynthetic surface area, which supports apical growth and reproductive development (7). These outcomes align with the findings of (22,23), reinforcing the positive influence of sulphur nutrition on yield-related parameters in groundnut crops.

The number of pop seeds was highest in T_{15} (5.04), followed by T_{14} (3.46), indicating a higher proportion of immature or unfilled pods. The lowest number of pop seeds was noted in T_{13} (1.25), suggesting better seed development. During the early stages of peanut development, calcium accumulates mainly in the cell wall, where it supports vital metabolic activities such as cell division and carbon-nitrogen metabolism (24). As the crop matures, a redistribution of calcium from the cell wall to the soluble and organelle-bound fractions occurs. Notably, gypsum application accelerates this shift, making calcium more accessible for physiological and metabolic functions, thereby further contributing to plant growth (12).

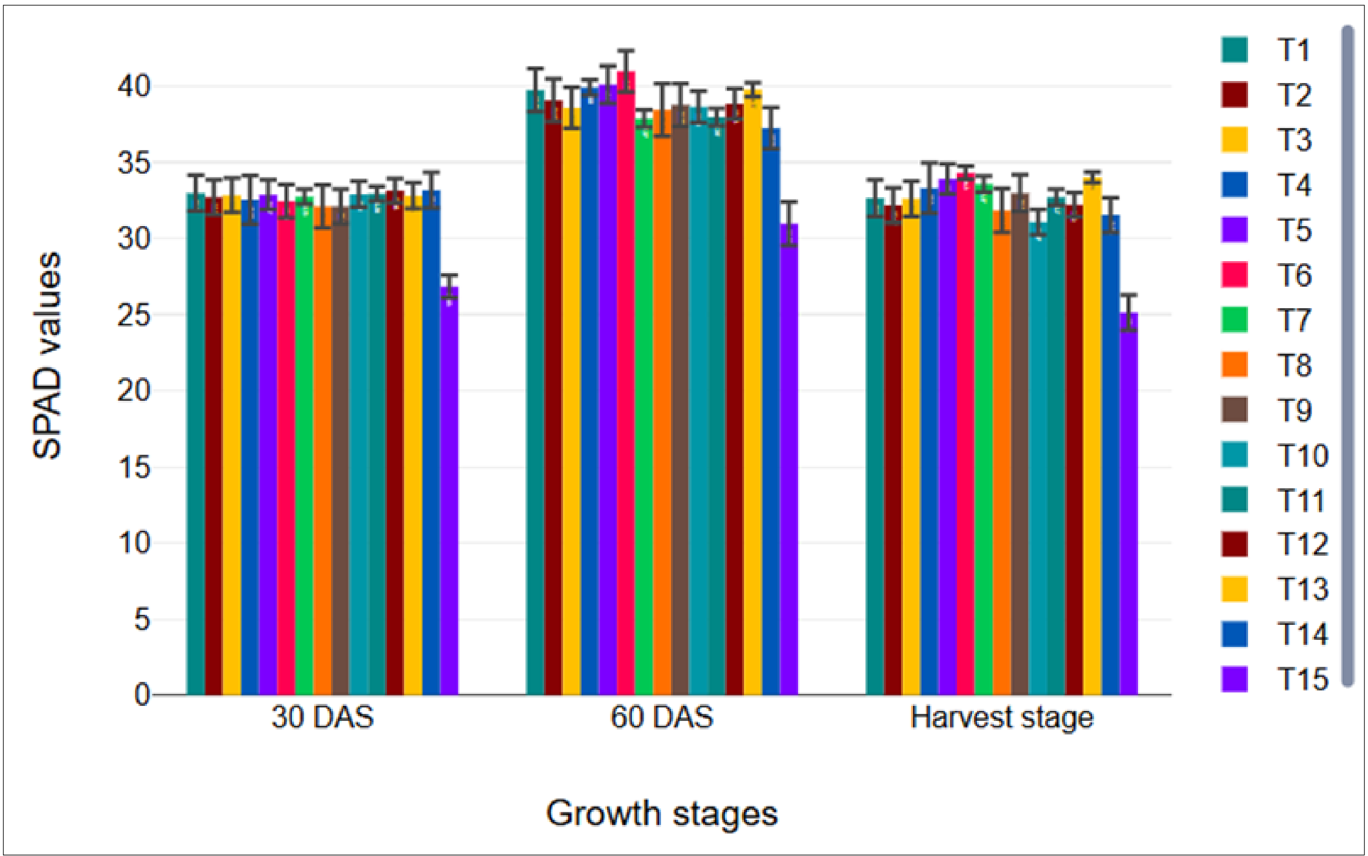

Fig. 2. Impact of foliar application of nano sulphur and nano calcium on SPAD readings at different growth stages in groundnut.

Table 2. Influence of foliar application of nano sulphur and nano calcium on total number of pegs, total number of pods, number pops seeds, total number of mature pods and peg pod conversion ratio

Treatments	Total number of pegs	Total number of pods	Number pops seeds	Total number of mature pods	Peg pod conversion ratio
T_1	34.01	23.42	3.20	20.22	68.89
T_2	34.79	24.05	3.63	20.42	69.23
T_3	36.04	24.99	3.38	21.61	69.34
T_4	35.98	24.99	3.05	21.94	69.65
T_5	36.76	26.61	3.00	23.61	70.57
T_6	37.88	27.58	3.19	24.39	72.85
T_7	33.38	23.11	3.49	21.12	69.24
T_8	32.38	22.47	3.55	20.42	69.57
T_9	33.45	22.99	3.32	21.17	68.73
T_{10}	32.04	22.22	3.25	20.47	69.47
T_{11}	32.92	22.67	3.08	21.54	68.93
T_{12}	33.61	23.34	3.11	22.36	69.48
T_{13}	36.25	26.10	1.25	24.85	72.08
T_{14}	30.78	20.15	3.46	15.36	65.46
T_{15}	24.25	15.50	5.04	10.46	63.92
SEd	**1.64**	**0.89**	**0.17**	**0.76**	**2.00**
CD (p=0.05)	**3.35**	**1.82**	**0.33**	**1.56**	**4.11**

Yield

The pod yield and haulm yield of groundnut varied significantly among treatments (Table 3). The highest pod yield was recorded in T_6 (2461 kg ha^{-1}), which was statistically on par with T_5 (2432 kg ha^{-1}) and T_{13} (2431 kg ha^{-1}). The lowest pod yield was observed in T_{15} (1325 kg ha^{-1}), which was significantly lower than all other treatments. Haulm yield followed a similar trend, with T_9 producing the highest haulm yield (4907 kg ha^{-1}), followed by T_1 (4893 kg ha^{-1}) and T_{14} (4847 kg ha^{-1}), while T_{15}recorded the lowest haulm yield (2833 kg ha^{-1}). Shelling percentage, as shown in Fig. 3, had the minimal variation among treatments, ranging from 67.12 % (T_{15}) to 68.80 % (T_6). However, the differences were not statistically significant. In terms of seed yield, the highest was recorded in T_6 (1701 kg ha^{-1}), followed by T_5 (1674 kg ha^{-1}) and T_{13} (1665 kg ha^{-1}). These treatments were significantly superior compared to the lowest seed yield in T_{15} (897 kg ha^{-1}). Split applications of sulphur, specifically at tillering and booting stages, significantly enhance biological and grain yield in wheat (25). In contrast, single applications, particularly at the tillering stage alone, resulted in lower yields. Another study have confirmed that dividing the sulphur dose, especially with one application before sowing and another at stem elongation, led to

Table 3. Influence of foliar application of nano sulphur and nano calcium on pod yield (kg ha^{-1}), haulm yield (kg ha^{-1}) and seed yield (kg ha^{-1})

Treatments	Pod yield (kg ha^{-1})	Haulm yield (kg ha^{-1})	Seed yield (kg ha^{-1})
T_1	2380	4893	1637
T_2	2351	4726	1606
T_3	2361	4770	1613
T_4	2373	4858	1614
T_5	2432	4771	1654
T_6	2461	4804	1683
T_7	2269	4733	1544
T_8	2238	4799	1524
T_9	2237	4907	1537
T_{10}	2236	4827	1522
T_{11}	2233	4864	1522
T_{12}	2237	4818	1523
T_{13}	2431	4794	1654
T_{14}	2231	4847	1529
T_{15}	1325	2833	871
SEd	**17.9**	**37.1**	**22.2**
CD (p=0.05)	**36.7**	**76.0**	**45.5**

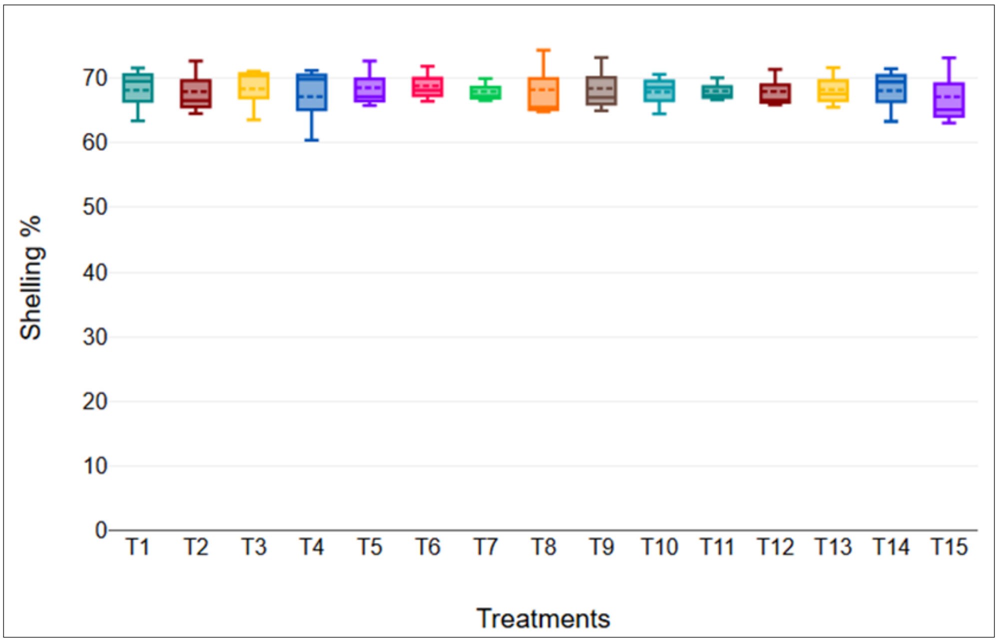

Fig. 3. Impact of foliar application of nano sulphur and nano calcium on shelling percentage in groundnut.

increased sulphur absorption and improved yield performance (26). Moreover, nano-sulphur offers unique advantages due to its high surface area and quantum size effects, which enable efficient light absorption across both visible and UV spectra. This enhances the performance of photosynthetic enzymes, chloroplast activity and the electron transport chain, ultimately improving ATP and NADPH synthesis and supporting higher rates of carbon fixation in the Calvin cycle (20). These all cause the increasing pod yield, seed yield and haulm yield of groundnut. These findings are consistent with the results reported by (27,28).

Oil content and oil yield

Oil content among the treatments ranged from 44.48 % (T_{15}) to 48.27 % (T_6) (Table 4). The highest oil content was recorded in T_6 (48.27 %), which was statistically on par with T_5 (48.13 %), T_{13} (48.10 %) and T_4 (47.92 %). The lowest oil content was observed in T_{15} (44.48 %). Oil yield followed a similar trend, with T_6 producing the highest oil yield (820.7 kg ha^{-1}), followed by T_5 (805.9 kg ha^{-1}) and T_{13} (800.9 kg ha^{-1}), all of which were significantly superior to the lowest yield observed in T_{15} (399.0 kg ha^{-1}). These results highlight the superior performance of T_6 in both oil content and oil yield, emphasizing its potential for high-quality groundnut production. In groundnut, sulphur supplementation not only supports vegetative and reproductive growth but also improves key quality traits such as oil and protein content (29). The improved nutrient uptake and metabolic efficiency driven by sulphur facilitate the biosynthesis of fatty acids, contributing to higher oil percentages. The synergistic effects of enhanced dry matter accumulation, efficient photosynthesis and optimised enzyme activities collectively result in improved oil yield and quality. Jagasia et al. were reported the same results (30).

Table 4. Influence of foliar application of nano sulphur and nano calcium on oil percentage and oil yield (kg ha^{-1})

Treatments	Oil (%)	Oil yield (kg ha^{-1})
T_1	47.11	771.5
T_2	47.26	758.8
T_3	47.34	763.4
T_4	47.92	773.6
T_5	48.13	796.0
T_6	48.27	812.5
T_7	46.07	711.1
T_8	46.13	703.2
T_9	46.41	713.2
T_{10}	46.28	704.7
T_{11}	46.15	702.2
T_{12}	46.26	704.7
T_{13}	48.10	795.5
T_{14}	45.00	688.1
T_{15}	44.48	387.3
SEd	**0.24**	**12.74**
CD (p=0.05)	**0.49**	**26.09**

The scatter plot displays two clusters based on oil yield (kg ha^{-1}) and oil content (%), identified through k-means clustering (Fig. 4). Cluster 1 (red) contains treatments (T_1-T_{14}) with higher oil yield and oil content, while Cluster 2 (blue) includes treatment (T_{15}) with comparatively lower values. The black 'X' markers represent the centroids of each cluster, indicating the average position of members within each group. This analysis highlights distinct groupings of treatments based on oil productivity, suggesting variation in their potential for oil yield improvement.

Principal Component Analysis (PCA) of agronomic traits

To visualise the multivariate relationships among the treatments and the contributing traits, a PCA was performed (Fig. 5). The biplot of the first two principal components (PC1 and PC2), which together explain a substantial portion of the total variance. The arrows represent the loadings of the original variables, while the blue dots represent the different treatments. PC1 accounts for the highest variance, separating treatments primarily along the horizontal axis, with the number of pop seeds showing the strongest positive contribution in this direction. This suggests that treatments positioned farther along the PC1 axis exhibit higher values for this trait. In contrast, traits like oil percentage, total number of pods and number of pegs load negatively on PC1, influencing treatments located to the left of the origin.

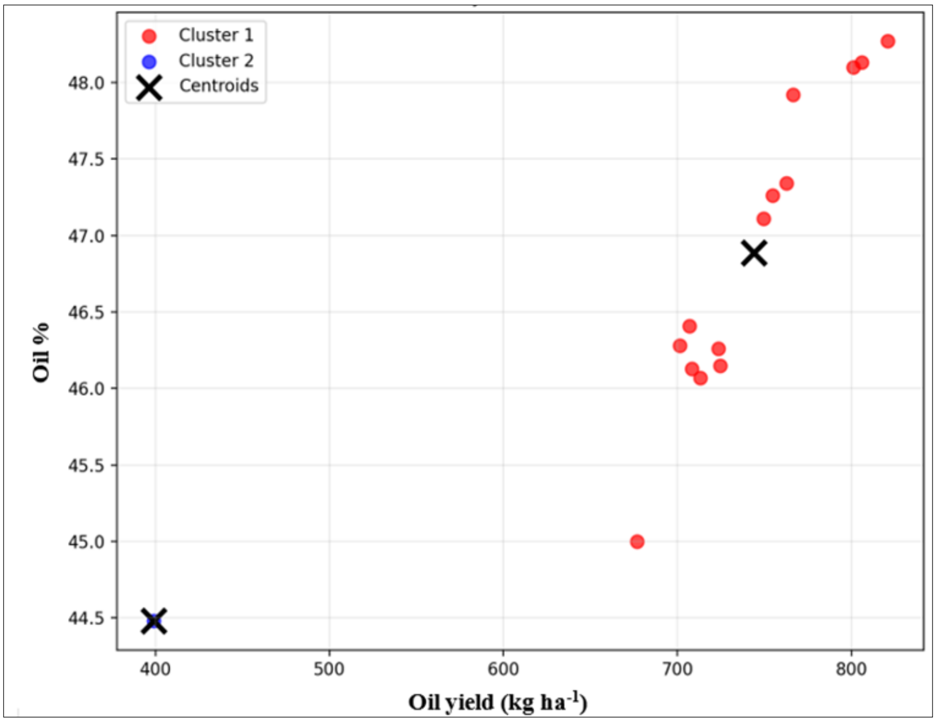

Fig. 4. Cluster analysis of oil percentage vs oil yield (kg ha^{-1}) in groundnut.

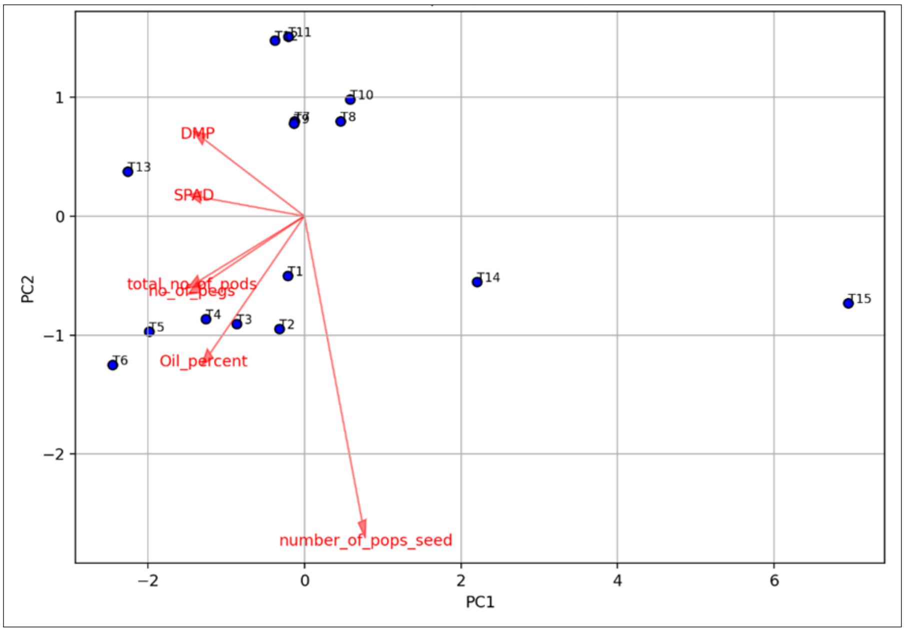

Fig. 5. Principal Component Analysis (PCA) of agronomic traits of groundnut.

PC2 captures additional variance and differentiates treatments along the vertical axis. Traits such as DMP and SPAD contribute positively to PC2, indicating their influence on treatments located higher on the plot. The relative angle between vectors indicates the correlation among variables; for example, the acute angles between SPAD, DMP and the total number of pods suggest a positive correlation among these traits. The spatial distribution of treatments shows diversity in trait expression. For instance, treatments T_{14} and T_{15} are separated from others along PC1, indicating distinct trait profiles, especially for the number of pop seeds. On the other hand, treatments such as T_4, T_5 and T_6 cluster more closely, reflecting similarities in their agronomic trait composition.

Correlation analysis

The correlation analysis revealed that the total number of pegs exhibited a strong positive association with all measured yield attributes in groundnuts (Fig. 6). The strongest correlation was observed between the total number of pegs and the total number of pods (r = 0.99), indicating a near-perfect linear relationship. This was followed by very strong correlations with oil yield (r = 0.97) and seed yield (r = 0.94), as well as a strong correlation with pod yield (r = 0.93). Although relatively lower, the peg-to-pod conversion ratio also demonstrated a strong positive correlation (r = 0.89). These relationships are further visualised in the heatmap (Fig. 6), where a colour gradient from lighter to darker red indicates increasing strength of positive correlation. This analysis underscores the critical role of peg development in determining groundnut productivity.

Multivariate analysis

The analysis demonstrated a consistently strong positive linear relationship between the total number of pegs and key yield parameters in groundnut (Fig. 7). The results indicate that an increase in the number of pegs significantly enhances crop productivity, as evidenced by high R^2 values and statistically significant relationships ($p < 0.05$) across all measured parameters.

Pod yield

$Y = 77.0381x - 334.7497 \quad (R^2 = 0.8698)$

The model indicates that approximately 87 % of the variation in pod yield can be explained by the number of pegs. For every additional peg, pod yield increases by around 77 kg ha^{-1}. The high R^2 (0.87), strong correlation (R = 0.93) and significant p-value highlight a strong relationship, suggesting peg formation is a critical driver of pod yield.

Total number of pods

$Y = 0.8783x - 6.1956 \quad (R^2 = 0.9821)$

Each additional peg corresponds to nearly one more pod, with a slope of approximately 0.88. The R^2 value of 0.98 indicates that peg number explains 98 % of the variation in pod number, suggesting a nearly perfect predictive relationship. The correlation coefficient (R = 0.991) and p-value further confirm the high reliability and significance of this relationship.

Seed yield

$Y = 53.8459x - 271.6232 \quad (R^2 = 0.8758)$

Seed yield increased linearly with peg number. Each peg contributes to an increase of about 54 kg ha^{-1} in seed yield. The model explains 88 % of the variation in seed yield, with a strong correlation (R = 0.936) and p-value reinforcing the importance of peg development in reproductive success.

Oil yield

$Y = 29.3336x - 265.667 \quad (R^2 = 0.9403)$

Oil yield also exhibited a strong positive relationship with peg number. Each additional peg increased to approximately 29 kg ha^{-1} in oil yield. The R^2 value of 0.94 and correlation coefficient (R = 0.970) and p-value indicate a highly reliable and statistically significant relationship, underscoring the importance of peg count in determining oil productivity.

Fig. 7 shows scatter plots with linear regression lines show strong positive relationships between the total number of pegs and yield components in groundnut, including pod yield (kg ha^{-1}), total pods, seed yield (kg ha^{-1}) and oil yield (kg ha^{-1}). High R^2 values confirm peg number as a strong predictor of productivity, with the number of pods showing the strongest correlation. These results highlight the importance of promoting peg formation to enhance yield and oil content in groundnut.

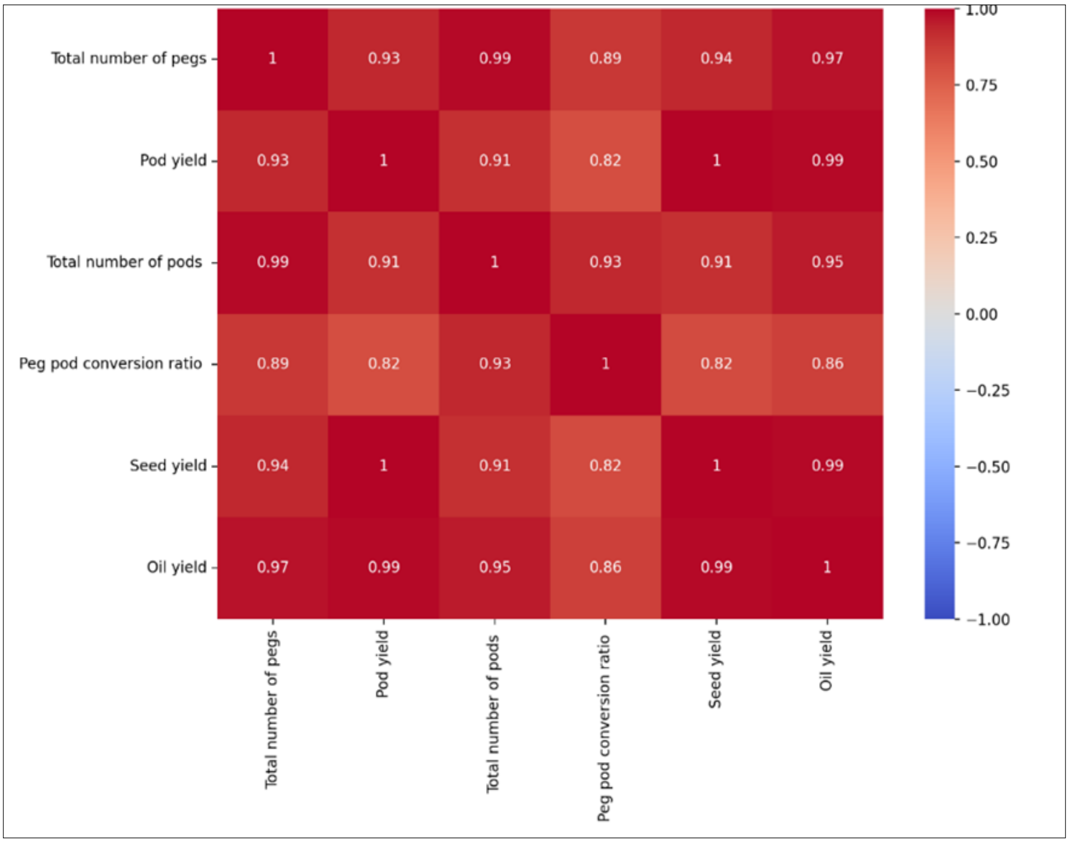

Fig. 6. Correlation heatmap analysis of the total number of pegs vs yield attributes.

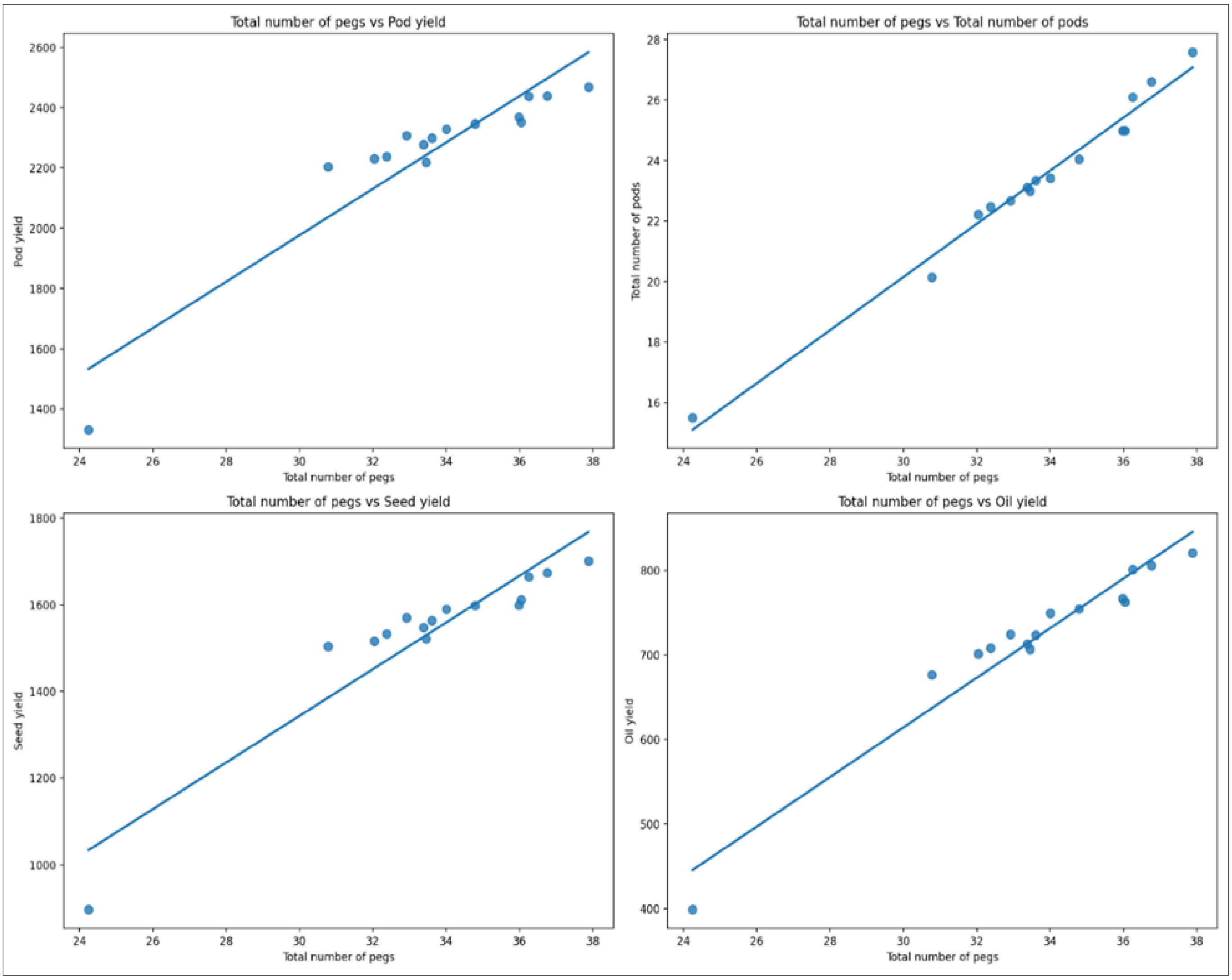

Fig. 7. Scatter plot with a linear regression relationship with the total number of pegs and yield attributes of groundnut.

Conclusion

The study demonstrated that foliar application of nano sulphur and nano calcium significantly influences the growth, yield and oil quality of groundnut. Among all treatments, nano sulphur at 200 ppm applied at both 30 and 45 DAS (T_6) was most effective, enhancing DMP, SPAD values, peg and pod formation and yield attributes. This treatment resulted in the highest pod, seed and oil yields, as well as superior oil content and performed comparably to the conventional gypsum-based treatment. Strong positive correlations between the number of pegs and key yield parameters further underline the importance of peg development in achieving higher productivity. These findings support the strategic use of nano fertilizers, especially nano sulphur, as an efficient and sustainable approach to improve nutrient use efficiency and crop performance in groundnut cultivation.

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Authors' contributions

KM prepared manuscript, SN, RR, RK and RSK participated in the sequence alignment and drafted the manuscript. SA quoted the references. SK and VV helped during collection of articles. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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