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Significance of secondary nutrients and their management in groundnut (*Arachis hypogaea* L.): A review

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Abstract
Groundnut ranks third among oilseeds production in India, contributing about 15% to the country's total vegetable oil production. It is predominantly cultivated in arid and semi-arid regions, largely under rainfed conditions. Compared to other crops, groundnut requires higher amount of secondary nutrients for optimal growth and productivity. In groundnut, yield losses due to deficiencies of secondary nutrients have been estimated at 27% for calcium, 30% for magnesium and 25% for sulphur. Calcium plays a crucial role in pod development and filling, while magnesium, being the central component of chlorophyll, is essential for photosynthesis. Sulphur is vital for the synthesis of amino acids and proteins, thereby improving oil quality. Despite its importance, the average productivity of groundnut in India remains below the global average. Therefore, optimizing secondary nutrient management is a key in reducing pop formation and enhancing both the yield and quality of groundnut pods and oil. In the recent past, nutrient management practices have evolved with the introduction of new nutrient sources and refined application strategies to better meet crop requirements. In this context, the present review compiles and analyzes existing literature on the importance of secondary nutrients and highlights recent advances in their management for enhancing groundnut poductivity.

Keywords: Calcium, groundnut, magnesium, secondary nutrients and sulphur

Introduction

Groundnut (*Arachis hypogaea* L.), commonly known as peanut, earthnut, monkey nut and manila nut, is the third most important oilseed crop in India next to soybean and rapeseed-mustard. It is a self-pollinated leguminous crop belonging to the family Fabaceae, with the ability to fix atmospheric nitrogen through symbiotic root nodules. The binomial *name Arachis hypogaea* is derived from the Greek words "Arachis," meaning legume and "hypogaea," meaning below ground, referring to its unique characteristic of underground pod development. Groundnut is highly valued for its rich edible oil content and is considered the third most important source of vegetable protein (Hoang *et al*., 2022) [23]. It is often referred to as the "King of oilseeds" due to its significant contribution to the edible oil industry and its wide range of uses (Sathya Priya *et al*., 2013) [51]. Additionally, it is regarded as a "poor man's crop" because of its role in ensuring food and nutritional security and supporting the livelihoods of millions of small and marginal farmers, particularly in arid and semi-arid regions. Being a day-neutral plant, groundnut can be grown in multiple seasons, including *kharif*, *rabi*, and summer (Anonymous, 2025) [4]. In India, however, nearly 85% of the cultivated area is under rainfed conditions during the kharif season.

Groundnut kernels are highly digestible and nutritionally rich, containing about 45% oil, 26–28% protein, 20% carbohydrates, and around 5% fibre (Fageria *et al*., 2010) [17]. Each gram of groundnut kernel provides approximately 5.8 calories, which is higher than that of sugar (4 calories) and wheat (3.5 calories). It is also a good source of essential minerals such as calcium, iron, and phosphorus, along with important vitamins including vitamin B_1 (thiamine), vitamin B_2

(riboflavin), vitamin B_3 (niacin), and vitamin E. Groundnut oil is composed of eight major fatty acids, contributing to its nutritional and industrial value (Biradar *et al*., 2013) [7]. In addition to the kernels, groundnut haulms are also valuable as livestock feed. They contain about 8–15% crude protein, 1–3% lipids and 9–10% minerals, making them suitable for use as fresh fodder, dried fodder, hay or silage. The production of groundnut is highly confined to Asian and African countries. Among the various oilseed crops cultivated in India, groundnut contributes around 19.05% of the oilseed area and about 27.91% of production (Anonymous, 2025) [4].

Globally, about 50% of groundnut production is utilized for oil extraction, 37% for confectionery purposes and around 12% for seed (Nurezannat *et al*., 2019) [44]. In India, groundnut production has increased more than threefold, rising from 3.48 million tonnes in 1950–51 to 11.81 million tonnes in 2024–25, despite little expansion in the cultivated area (Anonymous, 2025) [4]. This remarkable growth can be attributed to the sustained efforts of scientists and extension personnel in transferring technologies from research to field conditions. The development of high-yielding genotypes through breeding programs, along with improved nutrient management practices, has significantly contributed to enhancing yield potential.

Currently, India ranks first in terms of area (5.60 m ha) under groundnut cultivation (USDA, 2026) [65]. However, until 1992, India was the leading producer of groundnut globally, after which China surpassed it due to higher productivity levels, pushing India to the second position (Hauser, 2018) [21]. One of the major constraints limiting groundnut productivity in India is the inadequate and imbalanced use of nutrients. Groundnut is a nutrient-demanding crop and modern high-yielding varieties extract greater amounts of nutrients from the soil, making optimal mineral nutrition essential for sustaining high yields (Borah *et al*., 2017) [8]. Cultivation under conditions of nutrient deficiency or imbalance can lead to yield reductions ranging from 30% to 70%, depending on the severity and management practices adopted. In this context, the present review focuses on identifying key nutrient-related constraints in groundnut cultivation and outlines effective strategies for their management.

Need for secondary nutrients management in groundnut

A major share of groundnut cultivation in India is from rainfed conditions, where average productivity ranges from 500 to 1500 kg ha^{-1}, depending largely on rainfall distribution. The crop is grown across diverse soil types, including red and mixed red soils of Tamil Nadu, Karnataka, Andhra Pradesh, Rajasthan, Uttar Pradesh, and Madhya Pradesh, coastal alluvial soils of the Kutch and Saurashtra regions of Gujarat, lateritic soils of Karnataka and Odisha and alluvial soils of the Indo-Gangetic plains in Punjab, Haryana and Uttar Pradesh (Anonymous, 2025) [4]. Approximately one-third of the groundnut-growing area in India falls under calcareous and alkaline soils, which are typically deficient in iron and sulphur. Additionally, about 2.5 million hectares are located in high rainfall regions with acidic soils, which are commonly deficient in phosphorus, potassium, calcium, magnesium, boron and molybdenum. Being an energy-rich crop, groundnut extracts substantial amounts of nutrients from the soil, including not only primary nutrients but also secondary and micronutrients (Prakash *et al*., 2022) [46].

Deficiencies of secondary nutrients can cause significant yield losses in groundnut, estimated at 27% for calcium, 30% for magnesium and 25% for sulphur. Similarly, micronutrient deficiencies also lead to notable reductions in yield, ranging from 10–22% for iron, 13–15% for copper, 8–17% for manganese, 15–20% for zinc, 16–26% for boron and 13–19% for molybdenum (Meena *et al*., 2007) [41]. The increasing intensification of agriculture, continuous monocropping, and the indiscriminate use of straight fertilizers without proper soil testing have exacerbated deficiencies of secondary and micronutrients (Meena, 2007) [41]. Consequently, these nutrient imbalances have emerged as major constraints to achieving higher productivity in groundnut, highlighting the critical need for balanced and site-specific nutrient management strategies.

Soil nutrient reserves are rapidly depleted under continuous groundnut cultivation unless adequately replenished through manuring and fertilization. Ensuring a balanced and sufficient nutrient supply can enhance groundnut productivity by up to 50%, thereby helping to meet future demand (Devi *et al*., 2022) [12]. Groundnut exhibits a unique characteristic of positive geotropism. While flowering, pollination and fertilization occur above ground, the fertilized ovary develops into a peg (gynophore), which elongates and penetrates the soil to a depth of about 5–7 cm, where pod development takes place. The groundnut fruit, botanically termed a pod or lomentum, consists of seeds (kernels) enclosed within a protective pericarp or shell. Since pod formation occurs underground, yield assessment is difficult without uprooting the plants. In soils deficient in nutrients, especially during the critical pod development stage, plants exhibit poor nutrient uptake, leading to the formation of unfilled or "pop" pods and significant yield reduction (Senthamil and Tamilmounika, 2022) [52]. This makes groundnut particularly sensitive to deficiencies of secondary and micronutrients. Groundnut crop with a yield potential of 2.0–2.5 t ha^{-1} removes 60–80 kg ha^{-1} of calcium, 30–45 kg ha^{-1} of magnesium and 15–20 kg ha^{-1} of sulphur. In addition, it removes micronutrients such as iron (3–4 kg ha^{-1}), copper (30–40 g ha^{-1}), manganese (300–400 g ha^{-1}), zinc (150–200 g ha^{-1}), boron (140–180 g ha^{-1}) and molybdenum (8–10 g ha^{-1}) from the soil. Among these, calcium, sulphur, iron, zinc and boron are often the most limiting nutrients, due to their critical roles in pod filling and oil synthesis (Singh and Basu, 2005) [56].

Recent findings indicate that modern groundnut cultivars accumulate nutrients 30–40 days earlier than traditional varieties, leading to increased nutrient demand during early growth stages (Crusciol *et al*., 2021) [10]. Recognizing the importance of secondary nutrients, numerous studies have been conducted to develop efficient nutrient management strategies aimed at enhancing groundnut productivity and sustaining soil fertility.

Calcium

1. Role of calcium in plant physiology

Calcium is an essential nutrient responsible for maintaining cell membrane structure, integrity and permeability in plants. It occurs in the cell wall as calcium pectate and plays a crucial role in regulating cation uptake, osmoregulation, cell division and cell elongation (Jing *et al*., 2024) [27]. Calcium is also involved in stress signaling, enzymatic activity, protein synthesis and the translocation of carbohydrates from source to sink, thereby supporting overall plant growth and development (Kour *et al*., 2022) [33].

2. Calcium deficiency symptoms in groundnut

Calcium is an immobile nutrient within the plant. Hence, deficiency symptoms initially appear in actively growing tissues such as young leaves and terminal buds (Kadirimangalam *et al*., 2022) [28]. During the vegetative stage, deficiency results in pale green leaves that become distorted, cup-shaped and develop hook-like tips, eventually leading to the drying of terminal leaves. In groundnut, calcium has a unique role during reproductive development. Since pods absorb calcium directly from the surrounding soil, deficiency during pod formation leads to embryo abortion and the development of empty or unfilled pods, commonly referred to as “pops”. The presence of a blackened plumule within the seed is known as “black heart” (Yang, 2020) [71].

3. Critical limits of calcium in soil and plant

Adequate calcium concentration in groundnut leaves at 50–70 days after emergence ranges between 1.2 and 2.0%. The critical soil calcium level required is approximately 250 ppm in the root zone and 600 ppm in the pod formation zone (Jing *et al*., 2024) [27]. Additionally, a minimum calcium concentration of 400 ppm in seeds is essential to ensure optimal germination and seedling vigor.

4. Soil factors affecting calcium availability

Calcium availability in soil is influenced by soil type and pH. Calcareous soils with a pH greater than 7 are generally rich in calcium and a significant proportion of groundnut cultivation in India occurs in such soils (Singh, 2001) [57]. However, crops grown in acidic soils with low base saturation and high aluminum content often experience calcium deficiency, which adversely affects growth and yield (Jing *et al*., 2024) [27].

5. Calcium sources and its management strategies for groundnut

Various sources of calcium fertilizers are available for groundnut cultivation, including gypsum ($CaSO_4$ $2H_2O$), limestone ($CaCO_3$) and nano-calcium formulations (Hamza *et al*., 2021) [19]. Among these, gypsum is the most widely used source due to its dual role in supplying both calcium and sulphur. Additionally, the application of phosphorus through single super phosphate also contributes to calcium nutrition in groundnut (Kannan *et al*., 2016) [32]. Calcium management is particularly critical during the pod development stage in groundnut. Since calcium is directly absorbed by pods from the soil, fertilizers should be applied in the pod zone at peak flowering to ensure adequate availability (Janila *et al*., 2013) [27]. Proper placement and timing of calcium application significantly improve pod filling, reduce the occurrence of pops, and enhance overall yield and quality. The major sources of calcium fertilizers are presented in the table 1.

Table 1: The major sources of calcium nutrient

Source	Ca content (%)
Basic slag	33.9
Ca EDTA	3-5
Calcium ammonium nitrate (CAN)	5
Calcium chloride	39.1
Calcium nitrate	19
Gypsum	29.2
limestone	36-38
Rock phosphate	35
Single super phosphate	18-21
Triple super phosphate	12-24

5.1 Nano-technology in calcium nutrition

Recent advancements in nanotechnology have opened new avenues for improving calcium use efficiency in groundnut. In this line, Deepa *et al*. (2015) [11] demonstrated the successful phloem transport of nano-scale calcium oxide (CaO) particles (69.9 nm), suggesting their effectiveness as a foliar calcium source. Foliar application of nano-CaO significantly enhanced calcium content in roots, shoots and leaves, thereby correcting deficiencies. Similarly, Abdelghany *et al.* (2022) [1] reported that foliar spraying of calcium and boron nanoparticles at 200 ppm improved plant height, crop growth rate, 100-seed weight, shelling percentage, seed yield, oil content, and protein content. Furthermore, Prasad *et al*. (2022) [47] observed that combined application of nano-scale nutrients (nano-CaO + nano-ZnO + nano-SiO_2) at 350 ppm resulted in significantly higher pod yield (2934.44 kg ha^{-1}), representing an 18% increase over conventional fertilizers, along with improvements in yield attributes such as filled pods, flower-to-peg ratio, and haulm yield.

5.2. Foliar application of calcium sources

Foliar feeding of calcium has proven effective, particularly under stress conditions. Song *et al*. (2020) [62] reported that foliar application of $CaCl_2$ (15 mmol l^{-1}) alleviated low night temperature stress by enhancing growth, dry matter accumulation and photosynthetic efficiency. Similarly, foliar application of sorbitol-chelated calcium fertilizer at 1.60 g l^{-1} increased yield by 28.6%, fruit number by 46.8%, 100-kernel weight by 20.4%, fully developed fruits by 55.3%, and fat content by 5% (Liu *et al*., 2021) [40]. Additionally, Shete *et al*. (2018) [54] reported that foliar application of 2% $Ca(NO_3)_2$ improved growth and nutrient uptake, including both macro- and micronutrients.

5.3. Soil application of calcium fertilizers

Soil application remains the most widely adopted method for calcium supplementation. Hamza *et al*. (2021) [19] observed that the combined application of gypsum and calcium nitrate [$Ca(NO_3)_2$] resulted in the highest yield and superior quality traits. Calcium fertilizers such as lime and gypsum are commonly applied at rates ranging from 200 to 1000 kg ha^{-1}, depending on soil calcium status.

5.4. Gypsum as a key calcium source

Gypsum is the most commonly used calcium source in groundnut cultivation due to its dual role in supplying both calcium and sulphur. It is particularly effective when applied at the peak flowering stage and incorporated into the top 5–10 cm of soil, ensuring its availability in the pod formation zone. Adequate gypsum application enhances pod filling, reduces the incidence of pops and improves kernel quality. Ruhunuge *et al*. (2022) [50] reported that soil application of gypsum at 200 kg ha^{-1} along with recommended fertilizers in acidic soils (pH 4.4) significantly improved nut yield (2800 kg ha^{-1}) and kernel quality. Whereas, split application of slag-based gypsum (SBG) @ 625 kg ha^{-1} (50% at sowing + 50% at peg initiation) significantly enhanced pod, haulm, kernel, protein, and oil yield of groundnut compared to other treatments (Dhumgond *et al*., 2025) [13]. Further, it improved nutrient availability in post-harvest soil and recorded higher sulphur and calcium use efficiency and uptake efficiency over basal application.

5.5. Integrated nutrient management approaches

Integrated nutrient management (INM) strategies combining organic and inorganic sources have shown significant benefits. Dipankar and Dipak (2015) [15] reported that the application of FYM @ 5 t ha^{-1} along with lime (10% of lime requirement) and recommended NPK increased pod yield by 210% in acidic sandy loam soils. Such approaches improve nutrient availability, soil health, and long-term sustainability.

5.6. Alternative calcium sources
Alternative calcium sources such as oyster shell powder have also shown promising results. Kamara *et al.* (2017) [29] reported that application of 100 kg Ca ha^{-1} through oyster shell powder resulted in the highest seed yield of groundnut, indicating its potential as a low-cost and sustainable calcium source.

5.7. Calcium nutrition under abiotic stress
Calcium plays a crucial role in mitigating abiotic stresses, particularly temperature stress. Foliar application of calcium improves photosynthetic efficiency, enhances sink strength, and reduces stress-induced metabolic disruptions, thereby sustaining crop productivity under adverse conditions (Kour *et al.*, 2022) [33].

5.8. Calcium requirement and application strategy
Calcium demand in groundnut is highest during the pod filling stage. Therefore, timely application and proper placement of calcium fertilizers are critical. Shallow placement in the top 5–10 cm of soil ensures better availability to developing pods. Site-specific nutrient management based on soil testing is essential to optimize calcium use efficiency and maximize yield. The various reports pertaining to calcium fertilization in groundnut is listed in the Table 2.

Table 2: Sources and reports of calcium fertilization in groundnut

S. No.	Treatment	Results	Author
1	Foliar application of nano-CaO (69.9 nm)	Increased Ca content in roots, shoots, and leaves	Deepa *et al.* (2015) [11]
2	Foliar spray of Ca and B nanoparticles @ 200 ppm	Improved plant height, crop growth rate, 100-seed weight, shelling%, seed yield, oil and protein content	Abdelghany *et al.* (2022) [1]
3	Nano nutrients (nano-CaO + nano-ZnO + nano-SiO_2) @ 350 ppm	Improved pod yield by 18%	Prasad *et al.* (2022) [47]
4	Foliar spray of sorbitol-chelated Ca @ 1.60 g l^{-1}	Increased yield (by 28.6%), fruits $plant^{-1}$ (46.8%), 100-kernel weight (20.4%), full fruits (55.3%) and fat content (5%)	Liu *et al.* (2021) [40]
5	Foliar application of 2% $Ca(NO_3)_2$	Increased uptake of N, P, K, S, Ca, Mg, Fe, Mn, Zn and Cu	Shete *et al.* (2018) [54]
6	Gypsum @ 200 kg ha^{-1} + RDF (acid soil)	Highest nut yield (2800 kg ha^{-1}) and improved kernel quality	Ruhunuge *et al.* (2022) [50]
7	FYM @ 5 t ha^{-1} + lime + NPK	Increased pod yield by 210% in acidic sandy loam soil	Dipankar and Dipak (2015) [15]
8	Oyster shell powder @ 100 kg Ca ha^{-1}	Highest seed yield	Kamara *et al.* (2017) [29]

Magnesium
1. Role of magnesium in plant physiology
Magnesium is an essential secondary nutrient and a central component of the chlorophyll molecule, playing a crucial role in photosynthesis (Verbruggen and Hermans, 2013) [68]. It also acts as a cofactor for several key enzymes, including RUBISCO, PEPCO and other phosphorylating enzymes involved in carbohydrate metabolism (Tian *et al.*, 2021) [64].

2. Magnesium deficiency in soils
Magnesium deficiency in soils is commonly associated with nutrient imbalance, particularly when the calcium to magnesium (Ca:Mg) ratio exceeds 10–15:1. Such conditions are prevalent in acidic and sandy soils. In regions with high rainfall, magnesium is easily leached, further increasing the risk of deficiency and limiting its availability to plants (Guo *et al.*, 2016) [18].

3. Deficiency symptoms in groundnut
Magnesium is a mobile nutrient within the plant. Therefore, deficiency symptoms first appear in older leaves. The typical symptom is interveinal chlorosis, which begins at the leaf margins and gradually progresses towards the midrib. Severe deficiency may lead to reduced photosynthetic efficiency and premature leaf senescence (Singh *et al.*, 2004) [55].

4. Role of magnesium in protein synthesis
Magnesium serves as a structural component of ribosomes and is essential for protein synthesis (Verbruggen and Hermans, 2013) [68]. Its deficiency leads to a reduction in nitrogenous protein content and a relative increase in non-nitrogenous compounds, adversely affecting crop quality and metabolic functions (Tian *et al.*, 2021) [64].

5. Critical limits of magnesium in soil and plant
The critical level of available magnesium in soil for groundnut cultivation is approximately 15 ppm. The adequate range of magnesium concentration in leaves generally lies between 0.30 and 0.80% (Singh and Basu, 2005) [56].

6. Magnesium fertilizer sources
Magnesium can be supplied through various fertilizer sources such as magnesium sulphate ($MgSO_4$), dolomite and other magnesium containing compounds. The choice of source depends on soil properties, crop requirements and management practices. Details of major magnesium fertilizer sources are presented in Table 3.

Table 3: The major sources of magnesium fertilizers

Source	Mg content (%)
Dolomite	12-20
Epsom salt	10
Langbeinite	11
Mg chelate	2-4
Magnesium chloride	25
Magnesium nitrate	9
Magnesium oxide	55

8. Management strategies for magnesium in groundnut
Efficient magnesium management is essential for improving groundnut productivity, particularly in soils prone to deficiency. Ananth Kumar *et al.* (2016) [3] reported that soil application of the recommended dose of fertilizers (RDF) along with 20 kg MgO ha^{-1} and 5 kg borax ha^{-1} resulted in maximum pod and haulm yield. This improvement was attributed to the synergistic effect of magnesium and boron on growth parameters and

nutrient use efficiency. Magnesium nutrition also influences plant health, as deficiency has been shown to increase the severity of tikka disease in groundnut (Sharma *et al*., 2020) [53]. Based on experimental findings, Sireesha *et al*. (2022) [29] recommended the soil application of magnesium at 20 kg ha^{-1} as a basal dose, along with 40:50:60 kg ha^{-1} of NPK fertilizers, to achieve enhanced growth and higher yield.

Sulphur

1. Importance of sulphur in groundnut

Sulphur is recognized as the fourth major nutrient after nitrogen, phosphorus and potassium due to its crucial role in plant growth and metabolism. Although it is not a structural component of chlorophyll, sulphur is essential for its synthesis through its involvement in succinyl Co-A (Jamal *et al*., 2010) [24]. Approximately 90% of sulphur in plants exists in protein form as sulphur-containing amino acids such as cysteine (27% S), cysteine (26% S) and methionine (21% S) (Kamdi *et al*., 2014) [30]. Sulphur plays a significant role in root growth and nodule formation in legumes (Jat and Ahlawat, 2009) [26], and is also involved in the synthesis of vitamins such as biotin and thiamine. It contributes to oil synthesis by forming disulphide bonds between polypeptide chains (Kumar and Trivedi, 2011) [37]. Furthermore, sulphur enhances meristematic activity, cell division, elongation, and shoot development (Vishwanath *et al*., 2006) [69], leading to better rooting, increased leaf number and higher Leaf Area Index (Rajput *et al*., 2018) [49]. It also regulates plant metabolism through its influence on proteolytic enzymes (Najar *et al*., 2011) [42] and promotes apical growth and expansion of the photosynthetic surface (Piri *et al*., 2012) [45]. Sulphur also plays a key role in determining food quality, and its uptake and distribution are regulated by sulphate transporter gene families (Becana *et al*., 2018) [6].

2. Sulphur deficiency and critical limits

Sulphur deficiency symptoms first appear in young leaves as pale yellow or yellowish-green discoloration, including veins, which later turn white. The adequate sulphur concentration in leaves ranges from 0.20 to 0.35%, while deficiency occurs when levels fall below 0.17%. The critical level of available sulphur in soil is approximately 10 ppm. The critical level of $CaCl_2$ extractable S for deficiency in groundnut is 18 mg kg^{-1} (Kumar *et al*., 2019) [36]. Organic sulphur constitutes about 90% of total soil sulphur and acts as a major reservoir. Deficiency is commonly observed in calcareous and red lateritic soils, which dominate groundnut-growing regions in India. Coarse-textured sandy soils are particularly prone to sulphur deficiency due to leaching of sulphate (SO_4^{2-}) under high rainfall conditions (Hemesh *et al*., 2020) [22].

3. Sulphur requirement and dose optimization

The requirement of sulphur in groundnut varies with soil type and nutrient status, generally ranging between 20 and 60 kg ha^{-1} (Solaimalai *et al*., 2020) [61]. Higher doses are often required in sandy loam and alluvial soils. Dutta *et al*. (2015) [16] reported that application of 30 kg S ha^{-1} was comparable to 45 kg S ha^{-1} in terms of yield attributes and productivity. However, Ariraman *et al*. (2020) [5] observed that 60 kg S ha^{-1} resulted in superior growth parameters, including plant height, leaf area index, dry matter production and pod yield. The major sulphur fertilizers are listed in the Table 4.

Table 4: The major sulphur fertilizers

Source	S content (%)
Ammonium sulphate	24
Ammonium thiosulphate	26
Calcium thiosulphate	10
Ferrous sulphate	19
Elemental sulphur	100
Gypsum	19
Magnesium sulphate	13
Potassium sulphate	17
Pyrite	22-24
Slag-based gypsum	17.48
Zinc sulphate	18

4. Gypsum based sulphur management

Gypsum is the most widely used sulphur source in groundnut cultivation. Dileep *et al*. (2021) [14] reported that application of 40 kg S ha^{-1} through gypsum significantly improved growth, yield, and economic returns. Similarly, Yadav *et al*. (2019) [70] found that sulphur application at 60 kg ha^{-1} through gypsum enhanced yield attributes and profitability under semi-arid conditions. Split application of gypsum has shown superior results. Kannan *et al*. (2016) [32] reported that applying gypsum @ 400 kg ha^{-1} in two equal splits (basal and earthing up) maximized pod yield, oil content and oil yield in alfisols of Tamil Nadu.

Split application of gypsum @ 625 kg ha^{-1} (50% at flower initiation stage + 50% at pod development stage) along with 100% RDF recorded the highest oil content (48.43%) and improved protein content. However, it was on par with 100% RDF + CaMS Super @ 250 kg ha^{-1} (Kumar *et al*., 2024) [35]. Sulphur application enhanced oil synthesis by increasing the availability of sulphur-containing amino acids and enzymatic activity involved in oil formation. Aflatoxin content was lowest in split gypsum treatments and highest in the control, indicating improved quality with sulphur fertilization (Kankam *et al*., 2021) [31]. Acid value was highest under RDF alone, while iodine value decreased with sulphur application, with the control recording the highest iodine value.

5. Phosphogypsum and alternative sulphur sources

Phosphogypsum has also proven effective in groundnut cultivation. Naresha *et al*. (2018) [43] reported that application of phosphogypsum @ 500 kg ha^{-1} at flowering stage significantly increased pod yield, shelling percentage, and benefit-cost ratio. Further, Vaishnav *et al*. (2022) [67] demonstrated that split application of phosphogypsum (125 kg S equivalent ha^{-1}) improved growth parameters such as plant height, leaf area, and dry matter production. Alternative sources such as yellow gypsum and slag-based gypsum (SBG) have gained attention. Yellow gypsum, rich in Ca, S, Fe, Zn and Si, applied @ 625 kg ha^{-1} in split doses (basal and peg initiation), significantly improved growth, yield, and nutrient uptake (Laxmanarayanan *et al*., 2022) [38]. Similarly, SBG applied at the same rate enhanced yield, quality, and post-harvest soil fertility (Laxmanarayanan *et al*., 2020) [39].

6. Nano-sulphur and advanced fertilization approaches

Nano-sulphur has emerged as an efficient alternative to conventional sulphur fertilizers. Thirunavukkarasu *et al*. (2018) [63] reported that soil application of nano-sulphur @ 30 kg ha^{-1}

significantly increased sulphur uptake in roots, shoots, kernels, and shells. It also improved oil content (48.3%), crude protein (27.2%) and amino acid composition compared to conventional sulphur sources.

7. Elemental sulphur and fertilizer-based sources

Elemental sulphur is another effective source due to its slow-release nature. Sisodiya *et al*. (2017) [60] revealed that application of elemental sulphur @ 20 mg kg^{-1} soil resulted in higher nutrient uptake and yield. Single super phosphate (SSP) is also widely used as a sulphur source. Likewise, Singh and Sirothia (2020) [58] reported that application of sulphur @ 40 kg ha^{-1} through SSP increased pod, kernel and oil yield by 13.72%, 16.59% and 24.24%, respectively, compared to control, outperforming phosphogypsum and elemental sulphur.

8. Biofertilizers and microbial approaches

Biofertilizers containing sulphur-oxidizing microorganisms offer an eco-friendly approach to sulphur management. Hanif and Krishnamoorthi (2016) [20] reported that seed treatment with sulphur oxidizing bacteria (SOB) and Rhizobium, along with soil application of SOB and gypsum, significantly improved yield, shelling percentage, and benefit-cost ratio. Soil sulphur content also increased by 6.4–17.6%. Co-inoculation of *Thiobacillus* sp. and *Rhizobium* enhanced nodulation, biomass, oil content, and pod yield (Anandham *et al*., 2007) [2]. Such microbial approaches also contribute to biological nitrogen fixation and overall soil health (Chaudhary *et al*., 2022) [9].

9. Integrated sulphur management

Integrated nutrient management combining chemical fertilizers, organic inputs, and biofertilizers is essential for sustainable sulphur nutrition. The use of diverse sulphur sources tailored to soil conditions, along with split application strategies, ensures better nutrient availability during critical growth stages such as flowering and pod development.

Combined management of secondary nutrients

Godavari CaMS Super was released by Coromandel International Limited. It acts both as a soil conditioner and Fertilizer, containing Ca 15%, Mg 3% and S 8%, which is used @ 250 kg ha^{-1} in groundnut crop (Kumar *et al*., 2024) [35]. The table presents various fertilizer sources that supply calcium (Ca), magnesium (Mg), and sulphur (S) along with their approximate nutrient composition and suitability for different soil types. Calcium magnesium sulphate (CaMS) fertilizers offer a balanced supply of all three nutrients and are suitable for soils with multiple nutrient deficiencies. The different sources and fertilizers that supplies all the secondary nutrients are listed in the Table 5.

Table 5: Different nutrient sources and fertilizers supplying all the essential secondary nutrients

Fertilizer source	Ca (%)	Mg (%)	S (%)	Suitability for soils
Dolomitic gypsum	20–25	5–10	12–18	Acidic soils, improves Ca and Mg deficiency and supplies S
Calcium magnesium Sulphate (CaMS Super)	15–20	5–8	10–15	Suitable for balanced nutrient supply in deficient soils
Slag-based gypsum (SBG)	20–23	1–3	15–18	Acidic to neutral soils, improves soil fertility and structure
Yellow gypsum	20–23	1–2	15–18	Multi-nutrient deficient soils and also supplies Fe, Zn and Si
Dolomite + sulphur enriched	20–22	10–13	8–12	Acidic soils; corrects pH and supplies Ca, Mg and S
Phosphogypsum (with Mg traces)	20–22	0.5–1	15–18	Alkaline and sodic soils, and good for Ca and S supply
Custom blended Ca-Mg-S fertilizers	Variable	Variable	Variable	Site-specific nutrient management based on soil testing

Conclusion

Groundnut, being a nutrient-exhaustive and high-value oilseed crop, requires balanced and efficient management of secondary nutrients calcium, magnesium and sulphur to sustain productivity and quality. Deficiencies of these nutrients significantly limit yield and oil content, with calcium playing a crucial role in pod filling, magnesium in photosynthesis and enzyme activation, and sulphur in protein and oil synthesis as well as nodulation. The widespread occurrence of nutrient imbalances in diverse soil types, especially under rainfed conditions, further emphasizes the need for proper nutrient management. Recent advances such as nano-fertilizers, foliar nutrition, biofertilizers and alternative sources like gypsum and phosphogypsum have improved nutrient use efficiency and crop performance. Moreover, integrated nutrient management and site-specific approaches, combined with timely application during critical growth stages, have proven effective in enhancing yield, soil health and sustainability. Therefore, adopting a holistic and modern nutrient management strategy is essential to maximize groundnut productivity, improve quality and ensure long-term agricultural sustainability.

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