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Integrated Nutrient Management for Dragon Fruit Production: A Critical Review for Sustainable Productivity

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Abstract

Dragon fruit is an expanding commercial fruit but its nutrient recommendations remain fragmented and reported on inconsistent bases. This review synthesizes global and Indian studies (2000–2025) on macro/micronutrient requirements, interactions, integrated nutrient management (INM) and diagnostic tools. This paper provides a novel conceptual synthesis by tabulating fertilizer rates by elemental basis, compiling age-wise schedules, and analyzing yield-quality trade-offs. Evidence shows higher fertilizer doses do not consistently increase yield and may reduce fruit soluble solids. Split applications aligned with local fruiting patterns may improve nutrient-use efficiency, although optimal timing requires further field validation. Organic inputs complement mineral fertilizers, and micronutrient responses depend on soil pH and texture. Principal gaps include: (i) inconsistent nutrient bases and applications; (ii) scarce Mg, S, and micronutrient dose-response data; (iii) limited field evidence for acidic laterite soils; (iv) undocumented long-term INM effects on soil biology; (v) preliminary evidence for nano fertilizers and AI-based nutrient prediction.

Keywords: Dragon fruit, Integrated Nutrient Management (INM), Biofertilizers, Fertigation, Micronutrients.

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1. Introduction

Dragon fruit (*Hylocereus* spp.), also known as pitaya or strawberry pear, belongs to the Cactaceae family and originated from the tropical and subtropical regions of Central and South America (Pandey *et al.* 2023). Vietnam, China, and Indonesia dominate global production; Vietnam yields 1.4 million tonnes from 55,000 ha, exporting 80% to China (Das *et al.* 2025). In India, cultivation spans 14.5 thousand ha across Gujarat, Karnataka, Maharashtra, and northeastern states (Das *et al.* 2025).

Dragon fruit is a source of vitamin C, minerals, dietary fibre and phenolic compounds, and its antioxidant activity has been widely reported (Das *et al.* 2025). These compositional attributes are often cited as evidence of health benefits (Sethunath *et al.* 2025b); however, clinical benefits such as improved cardiovascular function and clinical trials remain limited. Commercial cultivation has been documented under contrasting environments, from 500 mm annual rainfall at Baramati to 2,500 mm in Tripura (Das *et al.* 2025), with successful production in Karnataka, Tamil Nadu, Assam, Uttar Pradesh, and Kerala. However, its adaptability to semi-arid environments applies strictly to well-drained soils with supplemental irrigation (Das *et al.* 2025).

Establishment of a plantation requires substantial investment in support systems and irrigation (Bura *et al.* 2025). Farmers also face high trellis costs, pollination requirements, anthracnose and stem canker, mealybugs and fruit flies, variable planting-material quality, price fluctuations and limited formal credit (Das *et al.* 2025; Kumar *et al.* 2022). Nutrient management is a key adjustable factor because it affects vegetative growth, fruit set, fruit size and sugar accumulation. Inadequate or imbalanced nutrition can reduce yield and quality and weaken long-term soil fertility; standardized recommendations remain limited in India (Rawat *et al.* 2022). Integrated nutrient management (INM), combining organic manures, mineral fertilizers and biofertilizers, may support nutrient balance, microbial activity and soil health (Srivastava *et al.* 2021; Bura *et al.* 2025). This is especially relevant because dragon fruit’s shallow adventitious roots can increase sensitivity to nutrient deficiency and nutrient loss under high rainfall (Das *et al.* 2025; Kakade *et al.* 2022).

Existing reviews cover nutrient management within broader discussions of crop production and sustainability (Ali *et al.* 2024) or alongside pest management (Belbase and Balaji Bhaskar 2025), while primary studies are largely short-term and site-specific. This review addresses gaps not consolidated in earlier reviews: non-comparable fertilizer bases and application units; limited age- and stage-wise schedules for this perennial crop; sparse evidence on Mg, S and micronutrients; insufficient regional evidence for acidic soils; and limited long-term assessment of INM effects on soil biology. It critically synthesizes global and Indian evidence, nutrient interactions, INM and emerging diagnostic tools.

2. Methodology

This critical narrative review synthesised literature on nutrient management in dragon fruit (*Hylocereus* spp. and *Selenicereus* spp.) published between 2000 and 2025. We searched Google Scholar in August and September 2026 using specific search strings: (“dragon fruit” OR “pitaya” OR “Hylocereus”) AND (“nutrient management” OR “fertilizer” OR “INM”

OR “biofertilizer” OR “fertigation”). Exact record counts were not retained. We examined reference lists of relevant publications to identify additional studies.

Peer-reviewed articles, relevant theses, and technical bulletins providing information on dragon fruit nutrient management, fertiliser treatments, plant growth, yield, fruit quality and related soil responses were considered. Publications lacking relevant information were excluded. Data on plant age, species or cultivar, planting density, plants per pole, soil properties, irrigation, experimental duration, nutrient sources, application methods, fertiliser rates, yield, and fruit-quality responses were extracted. Experimental details not reported in the original publications were not inferred.

Fertiliser rates were retained in their original units and nutrient bases. Where required, oxide-based rates were converted to elemental equivalents using $P = 0.436 \times P_2O_5$ and $K = 0.830 \times K_2O$. Rates expressed per plant, per pole, and per hectare were distinguished. Per-pole rates were converted to per-plant rates only when the number of plants per pole and the application basis were known. Unclear nutrient formulations or reporting bases were identified rather than assumed. Conflicting findings were interpreted in relation to differences in soil fertility, plant age, cultivar, production conditions, experimental design, and measured responses. Because the available studies differed in experimental methods, growing conditions, and reporting units, the evidence was synthesised narratively rather than through meta-analysis.

3. Nutrient management in dragon fruit

3.1. General principles of dragon fruit nutrient management

Dragon fruit nutrient management must account for its shallow root system, nutrient sensitivity and the need to balance organic and mineral inputs (Chakma *et al.* 2014). Most active roots are reported in the upper 30–40 cm, but maximum rooting depth varies with soil, moisture, plant age and production system (Kakade *et al.* 2022). Fertilizer placement should therefore target the active-root zone. Poor placement or delayed application can restrict growth and fruit set, particularly in coarse-textured soils with low nutrient retention (Samant *et al.* 2023).

Balanced fertilization is essential because both deficiency and excess can affect yield and fruit quality. High N may reduce soluble solids or alter peel colour, but responses depend on dose, application stage, cultivar and the quality trait measured. In West Bengal, soluble solids were highest in the unfertilized control and declined as NPK increased (Perween and Hasan 2019). In a Kerala container trial, soluble solids were also highest in the control but did not decline consistently with dose; the lowest fertilized dose produced the highest anthocyanin and, among fertilized treatments, total sugars (Sethunath *et al.* 2025a). These contrasting responses caution against universal dose–quality assumptions.

Frequent split applications are recommended because shallow roots are vulnerable to nutrient leaching, especially under high rainfall, and plants may produce three to four fruiting flushes from May to September (Das *et al.* 2025). Applications should be aligned with local flush timing and scaled to plant age and fruit load (Table 2). Key stages include establishment, when N and P support roots and shoots; pre-flowering and bud initiation, when K and B are important; fruit set and development, when K and Ca demand may rise; and post-flush

recovery, when N and P support renewed shoot growth. Fruit matures about 35–40 days after flowering (Das *et al.* 2025). However, schedules rarely derive from measured stage-wise nutrient uptake, leaving a major evidence gap.

3.2. Roles and interactions of essential nutrients

Nutrients are essential for specific developmental stages (Belbase and Balaji Bhaskar 2025). Potassium is the most accumulated macronutrient in the plant, followed by nitrogen and phosphorus (Karunakaran *et al.* 2025). Potassium application increased fruit yield by 20–24% in the first year and 64–70% in the second year (Fernandes *et al.* 2018).

Understanding the functional roles of essential nutrients in dragon fruit is incomplete without considering their interactive behaviour, as nutrient application often influences the availability, mobility, or uptake of other elements. Nitrogen (N) promotes vigorous vegetative growth, but excessive N application can suppress sugar accumulation and dilute anthocyanin content unless balanced with adequate potassium (K), which has been documented to counteract these effects in other fruit crops such as apple and grape, indicating a need to investigate similar mechanisms in dragon fruit (Sethunath *et al.* 2025a; Fernandes *et al.* 2018). High N inputs may also induce temporary phosphorus (P) immobilization in low-buffer soils by stimulating microbial demand, thereby reducing P availability during early root development (Srivastava *et al.* 2021). Conversely, adequate P application supports root initiation and flowering, while its uptake is constrained in alkaline soils or when Ca levels are excessive, leading to precipitation of insoluble calcium phosphates (Belbase and Balaji Bhaskar 2025). Potassium, which is heavily accumulated during flowering and fruit development, can antagonize magnesium (Mg) uptake at high application rates, often resulting in Mg-deficiency symptoms despite sufficient soil Mg levels (Sahu *et al.* 2022a). Similarly, Ca and Mg compete for uptake, and high Ca fertilization may restrict Mg absorption, influencing peel firmness and fruit quality (Sahu *et al.* 2022a). Micronutrient interactions are equally significant; for example, boron (B) is essential for pollen tube growth, yet its availability decreases in coarse-textured or drought-prone soils, and excessive Ca can further impair B mobility within plant tissues (Pandey *et al.* 2023). Zinc (Zn) efficiency decreases in alkaline soils and is antagonized by high phosphorus levels, whereas iron (Fe) chlorosis—common under high pH or waterlogging may be intensified by elevated Zn or Mn concentrations due to competitive inhibition at root-uptake sites (Mansingh and Padhan 2023). These interactive effects illustrate that nutrient management in dragon fruit must move beyond isolated nutrient recommendations and instead consider the complex balance among macronutrients and micronutrients to avoid immobilization, antagonism, or physiological imbalances that limit crop performance.

Nutrient	Role and Significance	Management Consideration
Nitrogen (N)	Essential for early vegetative growth. Increasing N generally increases shoot growth (Hariyanto <i>et al.</i> 2023).	Soluble solids declined as NPK dose increased in West Bengal (Perween and Hasan 2019) and were highest in the unfertilized control in Kerala (Sethunath <i>et al.</i> 2025a). A large yield loss on N omission (about 50%, versus 28% for P and 29% for K) was reported in an IPNI (2014) summary cited by (Karunakaran <i>et al.</i> 2025); the soil and location were not specified in that secondary source, so this should not be generalized to all soils or production systems.
Phosphorus (P)	Promotes root initiation and flower formation (Belbase and Balaji Bhaskar 2025).	Most efficiently absorbed at soil pH 6–6.5. Band placement is advised over broadcasting. Phosphate Solubilizing Bacteria enhance P availability (Mansingh and Padhan 2023).
Potassium (K)	Contributes to fruit quality and yield, especially during the flowering and fruiting through its role in ionic balance and cell elongation (Then 2012; Sahu <i>et al.</i> 2023).	The N–K counteraction of anthocyanin loss is documented in apple and grape (Sethunath <i>et al.</i> 2025a). Response depends on soil K status; K can antagonize Mg and Ca uptake.
Calcium (Ca)	Important for fruit firmness, quality and overall plant health (Belbase and Balaji Bhaskar 2025).	Soil application of 0–600 g Ca per hill per year in acidic soil (<i>Selenicereus monacanthus</i> , Bhubaneswar, Odisha) showed that 400 g per hill per year gave the highest yield, firmness, TSS and sugars, whereas pulp Mg, P, Mn and Fe were higher at 200 g (Sahu <i>et al.</i> 2022b). The unit is per hill, not per plant. The rate is trial-specific and should not be applied as a general recommendation.
Magnesium (Mg)	Constituent of chlorophyll and activator of many enzymes (Belbase and Balaji Bhaskar 2025; Marschner 2012).	No dragon-fruit-specific dose–response trial was identified in the literature screened. Risk of induced deficiency under high K or Ca; dolomitic lime or magnesium sulphate may be used in acidic soils (Sahu <i>et al.</i> 2022b).
Sulphur (S)	Constituent of amino acids, proteins and cofactors (Belbase and Balaji Bhaskar 2025).	Usually supplied incidentally through single super phosphate (about 11% S) or sulphate salts. In the trial of (Karunakaran <i>et al.</i> 2025) the soil was low in S and the requirement was met through single super phosphate.

Nutrient	Role and Significance	Management Consideration
Boron (B)	Crucial for proper ovule development, pollen tube growth, and fruit set (Pandey <i>et al.</i> 2023).	Soil and foliar B management has been shown to improve fruit set and quality (Belbase and Balaji Bhaskar 2025); B availability is reduced by leaching in acidic, high-rainfall soils.
Iron (Fe)	Fe chlorosis may lead to a 32% yield loss (Mansingh and Padhan 2023).	Ferrous sulphate (FeSO ₄) @ 10 g per liter of water can be applied as a foliar spray (Mansingh and Padhan 2023).

Table 1: Functional roles and management strategies of macro- and micronutrients in dragon fruit (*Hylocereus spp.*) cultivation

3.3. Diagnosis and technological prediction tools

Nutrient management involves proper diagnosis of deficiencies and utilizing modern technology for informed decisions:

Visual Diagnosis: Accurate diagnosis of nutrient disorders is crucial for effective nutrient management. Dragon fruit has no true leaves, so symptoms appear on the green stems (cladodes) and fruits. General indicators such as chlorosis, mottling, necrosis, stunted growth and premature senescence can provide preliminary clues about deficiencies (Nithila *et al.* 2023). Typically, N deficiency causes uniform pale-green to yellow stems with thin, slow growth; P deficiency causes stunted growth with poor root development and flowering; K deficiency causes weak stems, poor fruit size and quality; Mg deficiency causes yellowing of older stem tissue; Ca deficiency is associated with soft fruit and stem tissue and poor fruit firmness; B deficiency is associated with poor fruit set and corky or distorted growth; and Fe deficiency causes yellowing of young growth, which is common under high pH or waterlogging (Mansingh and Padhan 2023). Because these symptoms can be confused with disease, sunscald, waterlogging and chilling injury, they should be confirmed by soil and tissue analysis.

Soil Testing: Application of manures and fertilizers should be based on soil testing reports to determine specific requirements according to the soil type and fertility status. Continuous soil testing and tailored nutrient management are recommended to enhance fertility and productivity (Islam *et al.* 2024).

Remote Sensing and AI: Remote sensing technology can be used to detect soil moisture, nutrient stress and other soil stress conditions. In India, early IoT-based monitoring systems integrating soil moisture, EC, and nutrient sensors have been trialed for decision support in fruit crops, suggesting potential pathways for AI-assisted nutrient prediction in dragon fruit systems (Deepshikha 2023).

Artificial Intelligence (AI) is increasingly being integrated into dragon fruit production through computer vision, deep learning, and machine-learning techniques. With rising global demand, automated systems are needed to determine optimal harvest stages and evaluate fruit quality. High-resolution image datasets are now used to train deep-learning architectures such as ResNet50 and VGG-16, enabling applications ranging from automated harvest guidance to rapid quality grading in packhouses. These models can identify maturity stages and detect defects based on colour, shape, and surface characteristics. Reported results show that ResNet50 can classify immature and mature fruits with around 90% accuracy and distinguish fresh from damaged fruits with up to 98% accuracy (Khatun *et al.* 2024). Integrating CNN-based classification with IoT platforms has further enabled real-time field monitoring of ripe, raw, and deteriorating fruits, with high predictive scores (0.976–0.986), demonstrating the growing potential of AI-enabled decision-support tools in dragon fruit cultivation (Mulyadi *et al.* 2024).

3.4. Global nutrient management strategies for dragon fruit

Dragon fruit exhibits a shallow root system that facilitates efficient absorption of nutrients from the upper soil strata, but this also makes it sensitive to nutrient deficiencies (Kakade

et al. 2022). To achieve optimal growth and yield, balanced and frequent applications of organic manures and mineral fertilizers are recommended (Samant *et al.* 2023). Global nutrient recommendations for dragon fruit vary significantly across regions due to contrasting soil properties, climatic conditions, cropping intensities, and cultivar-specific responses (Belbase and Balaji Bhaskar 2025).

Regional fertilizer recommendations differ with soil, climate, cultivar and management, and should not be treated as directly interchangeable. For three-year-old plants in Vietnam, a secondary source reports annual applications of 540 g N, 720 g P and 300 g K plus 20 kg manure in four splits, but does not clarify whether P and K are elemental or oxide-based (Kakade *et al.* 2022; Tri *et al.* 2000, as cited by Sethunath *et al.* (2025a)). A Taiwanese practice reports about 100 g of 13-13-13 fertilizer plus 4 kg manure per plant every four months; three applications supply about 39 g N annually from the mineral fertilizer, with much nutrient supply likely coming from manure (Zee *et al.* 2004, as cited by Sethunath *et al.* (2025a)). In Bangladesh, 540 g N, 310 g P₂O₅ and 250 g K₂O per plant with 20 kg cow dung reportedly produced 32 t ha⁻¹ (Chakma *et al.* 2014). These reports vary in nutrient basis and detail; plant age is specified only for the Vietnamese rate, while cultivar, density, soil, irrigation and trial duration are often absent. Annual N recommendations range from approximately 56 g per plant (in container trials) or 100–113 g per plant in some trials to 540 g, reinforcing that rates cannot be pooled into a universal prescription. Original studies and local soil tests should guide interpretation.

3.5. Age-wise and stage-wise nutrient scheduling

Because dragon fruit is a long-duration perennial, nutrient doses should be scaled to plant age. The most detailed schedule available is that of (Das *et al.* 2025) for the north-eastern hill region (Tripura), in which fertilizer and manure doses increase from planting to full bearing at 36 months (Table 2). Bearing plants are thereafter fertilized in five splits per year: the last week of May (after the first flush), the last week of July (after the second flush), the last week of September (after the third flush), November (to encourage vegetative growth and bud initiation) and February (for flowering of the first flush of the following year). This schedule is derived from an extension article rather than a replicated trial, and should be validated locally; it is nonetheless useful because it links dose to age and to the fruiting calendar.

Plant age	Urea + SSP + MOP (g per plant per application)	Approximate N : P ₂ O ₅ : K ₂ O supplied (g)	Vermicompost + FYM (kg per plant)
1 month	13 + 12.5 + 5	6.0 : 2.0 : 3.0	1 + 1
6 months	26 + 25 + 10	12.0 : 4.0 : 6.0	2 + 3
12 months	40 + 38 + 15	18.4 : 6.1 : 9.0	3 + 4
15 months	52 + 50 + 20	23.9 : 8.0 : 12.0	4 + 5
18 months (before flowering)	65 + 63 + 24	29.9 : 10.1 : 14.4	5 + 6
21 months (fruit development)	78 + 75 + 27	35.9 : 12.0 : 16.2	6 + 7

Plant age	Urea + SSP + MOP (g per plant per application)	Approximate N : P ₂ O ₅ : K ₂ O supplied (g)	Vermicompost + FYM (kg per plant)
24 months	92 + 88 + 32	42.3 : 14.1 : 19.2	7 + 8
27 months	105 + 100 + 37	48.3 : 16.0 : 22.2	8 + 9
30 months	117 + 113 + 42	53.8 : 18.1 : 25.2	9 + 10
33 months	130 + 125 + 47	59.8 : 20.0 : 28.2	10 + 11
36 months (full bearing)	143 + 138 + 52	65.8 : 22.1 : 31.2	12 + 12

Table 2: Age-wise fertilizer and manure schedule for dragon fruit (Das *et al.* (2025))¹

3.6. Nutrient management strategies in India

The cultivation of dragon fruit in India has expanded significantly due to its profitability and market demand (Mansingh and Padhan 2023). However, productivity levels remain below those of major producing countries, primarily because of unstandardized nutrient practices. Integrated Nutrient Management has been identified as a promising approach to enhance yield and maintain soil health (Bura *et al.* 2025). Dragon fruit, a relatively new and commercially important climbing cactus in India, has demonstrated strong responses to well-planned nutrient management. However, detailed information on its optimal fertilisation regimes remains scarce in the existing literature (Rawat *et al.* 2022; Lakhanotra *et al.* 2025; Singh *et al.* 2022; Maurya *et al.* 2023).

¹(Note: The source text for manure doses reports minor internal inconsistencies regarding full bearing requirements; a standardized 12 kg FYM + 12 kg vermicompost dose is applied across all summaries here).

Region / state	Fertilizer recommendation (basis, age and conditions as reported)	Outcomes and benefits	Source
West Bengal (Mohanpur, Nadia)	N : P ₂ O ₅ : K ₂ O of 450 : 350 : 300 g per pillar (four plants per pillar) with 20 kg organic manure per pillar, in four splits (November, June, December, February); cv. Royal Moroccan Red, 2.5 × 2.5 m, sandy loam, planted March 2015, trial 2015–2017. The authors also state an equivalent of 113 : 88 : 75 g N : P ₂ O ₅ : K ₂ O per plant with 5 kg organic manure.	Highest yield (24.15 t ha ⁻¹) at this intermediate dose; higher doses reduced yield, and TSS was highest in the unfertilized control and declined with dose.	(Perween and Hasan 2019)
Uttar Pradesh (Lucknow)	15 kg FYM + 150 : 187.5 : 75 g NPK per plant + Azotobacter + phosphate-solubilizing bacteria (PSB). Basis (elemental or oxide) not stated; vegetative growth trial.	Significant improvement in vegetative growth parameters compared to the unfertilized control.	(Verma <i>et al.</i> 2019)
Jammu and Kashmir (Jammu)	Nitrogen supplied 50 : 50 through FYM and vermicompost, plus Azotobacter. Dose per plant not stated in the source reviewed.	Highest fruit weight (296 g), total soluble solids (10.86 °Brix) and cost–benefit ratio (1 : 4.73).	(Bura <i>et al.</i> 2025)
Uttar Pradesh (Ayodhya)	Per pillar of three plants: 200 g or 300 g water-soluble NPK (grade not stated) with 0.5% or 1% boron (source not stated), applied either conventionally in six instalments or half to the main roots and half to the aerial roots in three instalments, in alternate months from February 2021; 3-month-old plants at 4 × 3 m; alkaline silt loam (pH 8.3); two years.	Second year: highest yield (3.91 kg per pole), 14.0 fruits per pole and benefit–cost ratio (4.52) with 300 g NPK + 1% boron, half to main and half to aerial roots; no commercial yield in the first year.	(Pandey <i>et al.</i> 2023)
Maharashtra	Years 1–2: 500 : 500 : 300 g NPK per pole; year 3 onwards: 800 : 900 : 550 g NPK per pole. Per-pole basis (not interchangeable with per plant); P and K basis not stated.	Recommended for optimal growth and yield under local conditions.	(Kakade <i>et al.</i> 2020; Nangare <i>et al.</i> 2020)

Region / state	Fertilizer recommendation (basis, age and conditions as reported)	Outcomes and benefits	Source
Karnataka (Tumakuru)	N : P ₂ O ₅ : K ₂ O of 400 : 300 : 650 g per pillar per year (white-fleshed) and 750 : 400 : 347 g (purple-red), in four splits, plus 10 kg FYM + 1 kg neem cake per pillar. Four plants per pillar (about 100 : 75 : 162.5 and 175 : 100 : 87.5 g per plant) at 3.0 × 2.5 m; planted 2017, yields recorded 2020–21 to 2022–23; clay loam, pH 6.5, high available K, low N and S; about 800 mm rainfall, drip irrigation.	Predicted maximum yields of 25.5 t ha ⁻¹ (white-fleshed) and 37.1 t ha ⁻¹ (purple-red); treatments differed significantly only in the white-fleshed type.	(Karunakaran <i>et al.</i> 2025)
North-eastern region (Tripura)	Age-wise schedule (Table 2); from year 3, five splits of urea 143 g + SSP 138 g + MOP 52g with 12 kg FYM + 12 kg vermicompost per plant; VAM and Azotobacter (50 g each) at planting; foliar 19 : 19 : 19 at 2 g L ⁻¹ (January, August) and Zn 0.1% + B 0.5% sprays (June–August). Four plants per pole, 2 m × 2 m; rainfall up to about 2,500 mm.	Reported yield 25–35 kg per pole (62–85 t ha ⁻¹ as reported) under good management; extension article, not a replicated trial.	(Das <i>et al.</i> 2025)
North-eastern region (Mizoram)	INM: 500 : 300 : 250 g NPK per plant per year with Azotobacter, PSB and potash-solubilizing bacteria (KSB) (100 g per plant per year). Basis not stated; cluster demonstration.	Enhanced vine length, thickness and fruit yield.	(Kumar <i>et al.</i> 2022)
Assam	Organic: FYM (15 kg), vermicompost (5 kg), rock phosphate (200 g) and PSB (100 g) per plant; acidic soil.	Highest yield (4.76 t ha ⁻¹); improved TSS and ascorbic acid.	(Sahu 2023)
Odisha(Bhubaneswar)	Biofertilizer: 50 g arbuscular mycorrhizal fungi (AMF) per plant; acidic soil.	Enhanced soil health, root colonization, nutrient content, fruit yield and quality.	(Sahu <i>et al.</i> 2025)

Region / state	Fertilizer recommendation (basis, age and conditions as reported)	Outcomes and benefits	Source
Kerala (Thrissur)	Per pole (two plants per pole, 2 m × 2 m; plants in 100 L containers with a potting medium; cv. Cambodian Red; planted October 2022; trial 2022–2024; four splits): high dose N 337.5 : P ₂ O ₅ 262.5 : K ₂ O 225 g (about 337.5 g N, 114.5 g P, 186.8 g K); medium dose 225 : 175 : 150 g; low dose 112.5 : 87.5 : 75 g (about 112.5 g N, 38.2 g P, 62.3 g K); unfertilized control.	High dose: highest yield (15.29 kg per plant), fruit weight, shelf life and flushes. Low dose: yield on par (12.75 kg per plant), highest flowers, anthocyanin and total sugar. TSS highest in the control.	(Sethunath <i>et al.</i> 2025a)

Table 3: Regional fertilizer recommendations and their efficacy in India

3.7. Nutrient management strategies for dragon fruit in Kerala

Dragon-fruit cultivation is expanding in Kerala, but nutrient-management evidence remains limited. A survey of ten orchards in four districts grouped farms into establishment (0–2 years), yield-increasing (2–4 years) and yield-stabilizing (>4 years) phases; fertilizer and manure accounted for about 51–58% of annual maintenance costs in bearing orchards (Sethunath *et al.* 2025b). The identified dose–response trial was conducted at Vellanikkara, Thrissur, from 2022 to 2024 on Cambodian Red plants grown in 100-L containers with potting medium, two plants per pole at 2×2 m spacing, and four split applications (Sethunath *et al.* 2025a). The high treatment (337.5:262.5:225 g N:P₂O₅:K₂O per pole) produced the highest mean yield (15.29 kg per plant), heaviest fruit (492 g), longest shelf life (7 days) and most flushes. The low treatment (112.5:87.5:75 g per pole) yielded 12.75 kg per plant, statistically on par with the high treatment, and produced the highest anthocyanin and total sugar among treatments; soluble solids were highest in the unfertilized control. The first season was inconclusive because only one split preceded it (Sethunath *et al.* 2025a).

Kerala-specific field evidence is scarce, and the available dose–response trial used container potting medium rather than field soil; its rates should not be assumed to apply to lateritic soils. Results from other high-rainfall regions may inform hypotheses, but Kerala-specific field trials are needed to test nutrient retention, micronutrient behaviour and fertigation schedules. Although lateritic, acidic and high-rainfall conditions are important in parts of Kerala, the state also contains alluvial, coastal sandy and black soils with different pH, texture and nutrient retention. Soil testing at each site should therefore precede fertilizer selection (Sethunath *et al.* 2025a).

The Kerala trial illustrates a yield–quality trade-off: the highest dose improved fruit size and shelf life, but yield at one-third of that rate was statistically comparable, and soluble solids did not increase with fertilizer dose. In West Bengal, yield peaked at an intermediate dose while soluble solids declined as the dose increased (Perween and Hasan 2019). Neither trial reported dose-specific economic returns, so the highest yield or fertilizer rate cannot be assumed to be most profitable. In the Kerala orchard survey, mean yield was about 21 t ha^{−1} (range 7–32), average farm-gate price was 174 kg^{−1} (120–200), and the benefit–cost ratio fell from 4.29 at the average price to 2.96 at the lowest price; none of the sampled farmers exported fruit (Sethunath *et al.* 2025b). As production expands and price pressure increases, returns will depend on fruit size and eating quality as well as yield. Until economic evidence improves, farmers should avoid doses unsupported by soil tests and compare any quality or shelf-life premium with added input costs; moderate split applications with organic inputs are a cautious starting point.

3.8. Micronutrient management

Micronutrients such as B, Zn and Fe are critical for dragon fruit physiology, particularly for pollen germination, chlorophyll synthesis, and sugar translocation. Boron deficiency can lead to poor fruit set, while zinc improves enzyme activity and photosynthetic efficiency. In a two-year trial on newly planted vines at Ayodhya (alkaline silt loam, pH 8.3, 0.32 ppm B), 300 g of water-soluble NPK with 1% boron, fed half to the main roots and half to the aerial roots, gave the highest second-year yield (3.91 kg per pole), significantly more than the same

NPK feeding without boron (3.37 kg) (Pandey *et al.* 2023). The paper does not state the NPK grade, the boron source or the volume applied, so this rate cannot yet be converted into a field recommendation. Foliar sprays of 0.5% zinc sulphate (ZnSO_4) and 0.3% boric acid at flowering stages have been found to improve yield and fruit quality significantly (Ali *et al.* 2024). To correct Fe deficiency, ferrous sulphate (FeSO_4) @ 10 g per liter of water is recommended as a foliar spray (Mansingh and Padhan 2023).

Micronutrient behaviour is strongly shaped by nutrient interactions and soil conditions. Antagonistic interactions include high P suppressing zinc uptake, excess K inhibiting Mg and Ca uptake and elevated Ca reducing B mobility within plant tissues. In contrast, organic matter can improve Fe availability through chelation. High-pH or calcareous soils reduce the solubility of Fe, Zn and Mn, leading to chlorosis, whereas acidic, high-rainfall soils which are common in Kerala and parts of northeastern India promote leaching and reduce B availability. Sandy soils lose micronutrients rapidly because of low retention capacity, while clay-rich soils may fix Zn and limit its uptake (Mansingh and Padhan 2023).

3.9. Integrated Nutrient Management

FYM, vermicompost, and composts enhance organic carbon and water-holding capacity, while mineral fertilizers supply immediate nutrients. Biofertilizers such as Azotobacter, phosphate solubilizing bacteria (PSB) and potassium solubilizing Bacteria (KSB) mobilize nutrients, thereby, improving nutrient uptake efficiency (Bura *et al.* 2025). In a trial in West Bengal, an intermediate dose of mineral fertilizer (N : P_2O_5 : K_2O of 450 : 350 : 300 g per pillar) combined with 20 kg of organic manure per pillar gave the highest yield (24.15 t ha⁻¹) (Perween and Hasan 2019); that trial, however, did not include an organic-manure-free treatment, so the contribution of manure cannot be separated. INM can improve soil properties, leading to long-term enhancements in both soil quality and crop productivity, although current evidence remains short-term and site-specific.

However, its performance is influenced by several limitations: the quality and decomposition rate of organic inputs vary widely, making nutrient release unpredictable, particularly in high-rainfall regions where leaching is significant. INM also demands higher labour and consistent availability of organic materials such as FYM and vermicompost, which may be insufficient for large plantations. Additionally, the effectiveness of biofertilizers depends on soil pH, moisture, and competition with native microbes, reducing their reliability in acidic or waterlogged soils. These constraints highlight the need for region-specific INM protocols and systematic evaluation of input combinations across diverse agroecological conditions (Sahu *et al.* 2025).

3.10. Utilizing organic and biological sources

Organic amendments such as FYM, vermicompost and compost can increase soil organic carbon, water-holding capacity and microbial activity, supporting nutrient mineralization. Biofertilizers such as Azotobacter, phosphate-solubilizing bacteria (PSB) and potassium-solubilizing bacteria (KSB) may mobilize nutrients, while arbuscular mycorrhizal fungi (AMF) can extend effective root exploration and support P and micronutrient uptake. These mechanisms may improve soil structure, rhizosphere function and nutrient cycling, but outcomes

depend on input quality, soil conditions and field establishment ([Dey *et al.* 2025](#)). Application rates, efficacy evidence and limitations are summarized in [Table 4](#).

Input	Application rate and method	Evidence of efficacy	Important limitations
FYM	12 kg per plant in an organic mix (Assam; (Sahu 2023)); 11–12 kg per plant in bearing plants (Das <i>et al.</i> 2025); 10 kg per pillar with 1 kg neem cake (Karunakaran <i>et al.</i> 2025). Applied in the root zone, in splits with fertilizer.	Highest yield (4.76 t ha ⁻¹) with an organic mix (Sahu 2023); added to acid soils with other manures it can reduce Al toxicity (Mansingh and Padhan 2023).	Variable quality and decomposition rate; bulky; supply may be inadequate for large plantations.
Vermicompost (VC) and enriched compost	5 kg per plant (Sahu 2023); 12 kg per plant (Das <i>et al.</i> 2025). N supplied 50 : 50 through FYM and VC (Bura <i>et al.</i> 2025).	Improved nutrient levels and water retention; highest fruit weight, TSS and cost–benefit ratio with FYM + VC + Azotobacter (Bura <i>et al.</i> 2025).	Cost and availability; nutrient release unpredictable under high rainfall.
Mustard oil cake	Used in the organic nutrient mix (Sahu 2023).	Contributes to the organic mix that gave the highest yield (Sahu 2023).	Single trial; rate and individual effect not separated.
Rock phosphate	200 g per plant with PSB (Sahu 2023).	Used in organic formulations that improved yield, TSS and ascorbic acid in acidic soil (Sahu 2023).	Slow release; mainly suited to acidic soils.
Azotobacter, PSB, KSB	100 g per plant per year (Mizoram; (Kumar <i>et al.</i> 2022)); Azotobacter 200 g + phosphate-solubilizing microorganisms 100 g + Azospirillum 200 g + potassium mobilizer 100 g (Dey <i>et al.</i> 2025); 50 g Azotobacter at planting (Das <i>et al.</i> 2025).	Enhanced nutrient availability and uptake; increased vegetative development (Dey <i>et al.</i> 2025).	Performance depends on soil pH, moisture and competition with native microbes; generally should not be mixed with inorganic fertilizers (Bura <i>et al.</i> 2025).
Arbuscular mycorrhizal fungi (AMF)	50 g per plant (Odisha, acidic soil; (Sahu <i>et al.</i> 2025)); VAM 50 g at planting (Das <i>et al.</i> 2025).	Improved soil enzyme activity, root colonization, P mobilization, nutrient content, yield and fruit quality (Sahu <i>et al.</i> 2025).	Inoculum quality and field establishment are variable.

Input	Application rate and method	Evidence of efficacy	Important limitations
Biochar	5 kg biochar with 3 L cow urine per plant (Begum <i>et al.</i> 2024).	Better flowering and fruiting performance; improves soil properties and carbon sequestration.	Single trial; effects depend on feedstock and soil; cost.

Table 4: Organic, mineral, and biological inputs and their functional roles in dragon fruit

3.11. Use of nano fertilizers

Nano-fertilizers have been proposed as an option to enhance crop productivity while supporting soil health. For dragon fruit, evidence is limited to a single vegetative-growth trial comparing with urea, FYM and vermicompost; 6 mL L⁻¹ was reported to promote vegetative growth (Maurya *et al.* 2023). Claims that nano urea increases nitrogen availability above 80% were excluded because they could not be verified from primary dragon-fruit data. Nitrogen availability, absorption, use efficiency and fertilizer recovery are distinct parameters and none has been established for nano urea in dragon fruit. Because nano urea is applied as a foliar spray, its effects should not be attributed to soil pH; the influence of soil conditions remains unknown. The 6 mL L⁻¹ concentration should be treated as a hypothesis for field testing, not as a recommendation.

3.12. Fertigation based management

Fertigation is the application of fertilizers through irrigation and can improve nutrient placement, application timing and nutrient use efficiency when water and nutrient delivery are carefully managed (Belbase and Balaji Bhaskar 2025). IoT-based fertigation systems enable real-time monitoring of soil EC and pH, allowing precise nutrient management that reduces losses and environmental impact, in line with sustainable and climate-resilient agriculture (Ali *et al.* 2024). Drip irrigation with four drippers per four plants, delivering 6–8 L per hour, is used in Tripura (Das *et al.* 2025), providing a practical basis for stage-wise fertigation.

3.13. Management of problem soils

3.14. Acidic soil management

Soil acidity is classified according to standard ranges (e.g., USDA Soil Survey Manual): soils with pH 4.5–5.0 are very strongly acidic, 5.1–5.5 are strongly acidic, 5.6–6.0 are moderately acidic, and 6.1–6.5 are slightly acidic (Soil Science Division Staff 2017). Liming is most relevant to strongly acidic soils, where Al toxicity and Ca, Mg and P limitation occur; moderately to slightly acidic soils usually require only maintenance liming guided by exchangeable acidity. Liming can increase soil pH, reduce aluminium toxicity and improve the availability of certain nutrients (Belbase and Balaji Bhaskar 2025). However, the lime requirement and target pH should be determined from soil-test results, because excessive liming may reduce the availability of micronutrients (Das *et al.* 2025). In Assam, where soils are strongly acidic, the combined application of FYM, vermicompost, rock phosphate, and PSB significantly increased fruit yield, total soluble solids, and ascorbic acid content, demonstrating the effectiveness of organic amendments in reducing acidity-induced nutrient limitations (Sahu 2023).

3.15. Saline soil management

Dragon fruit is relatively tolerant to moderate salinity and can grow in soils with an electrical conductivity (EC) of up to 12 dS m⁻¹ (Kakade *et al.* 2025). However, long-term exposure

to high concentrations of soluble salts (Na, K) can negatively affect nutrient efficiency by causing osmotic stress, restricting water absorption and the uptake of vital cations like Ca^{2+} and Mg^{2+} (Belbase and Balaji Bhaskar 2025).

4. Conclusion

This review demonstrates that effective nutrient management in dragon fruit depends on balanced macronutrient supply, targeted micronutrient application, and the integration of organic and biological inputs that enhance soil structure and microbial activity. Evidence from global and Indian studies shows that potassium plays a dominant role during flowering and fruit development, while integrated nutrient-management approaches combining FYM, vermicompost, and microbial inoculants can improve yield, fruit quality, and soil health, though current field evidence is often short-term and site-specific. Fertigation enabled sensor-based monitoring offers a promising avenue for precise, stage-specific nutrient delivery in diverse Indian production systems.

Despite these advances, several challenges remain. Nutrient recommendations across Indian regions are still fragmented, and limited data exist on micronutrient dynamics in acidic, lateritic, and high-rainfall soils. Long-term studies on soil biological responses to INM, as well as controlled evaluations of nano-fertilizers, remain scarce. Future research should focus on refining fertigation schedules through AI-enabled decision tools, and establishing region-specific INM protocols that account for soil type, rainfall pattern, and cultivar behaviour. Addressing these gaps will be essential for enhancing productivity, improving nutrient-use efficiency, and supporting the expansion of sustainable dragon-fruit cultivation in India.

5. Challenges

Dragon fruit production encounters multiple constraints related to environmental, technological, and farm economics. Yields remain lower in India than in major producing countries due to the lack of standardized nutrient-management practices tailored to diverse soil and climate conditions (Rawat *et al.* 2022). Technological barriers also exist, as the development of reliable AI-based monitoring and grading tools is hampered by low-quality field images affected by uneven lighting and complex backgrounds (Khatun *et al.* 2024). Socioeconomic challenges, including limited access to formal credit, dependence on informal lenders, and widespread rural poverty, further restrict farmers' ability to invest in improved practices, contributing to financial vulnerability and reduced overall productivity (Kumar *et al.* 2022).

6. Future directions

Future progress in dragon fruit cultivation will depend on refining Integrated Nutrient Management strategies that combine mineral fertilizers with organic inputs to improve nutrient efficiency and yield stability (Kumar *et al.* 2022). Innovations such as nano urea, alongside optimized fertilizer ratios and irrigation schedules, require rigorous field testing to determine their actual efficacy while maintaining soil health conditions (Maurya *et al.* 2023). Advancing genetic improvement through germplasm evaluation, stress-tolerant genotype selection,

and modern biotechnological tools can support the development of superior cultivars. At the same time, expanding high-quality image datasets will be essential for developing accurate automated systems for fruit maturity assessment and quality grading ([Khatun *et al.* 2024](#)).

i Declaration of any AI tool

Artificial intelligence (AI) tools were used solely for grammatical correction and language improvement. The authors reviewed and verified all content and take full responsibility for the accuracy and integrity of the manuscript.

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