Nutrient strategies for pest resilience in plants: A Review

ABSTRACT

Sustainable agriculture plays a vital role in modern farming, addressing concerns of traditional pesticides, which raise issues related to safety, environmental impact, and resistance. Consequently, alternative insect pest management methods, including nutrient-based approaches, have gained prominence. However, understanding the relationship between nutrients and plant diseases remains a complex challenge. This review synthesizes recent insights on the impact of specific nutrients (N, P, K, Mn, Zn, B, Cl and Si) on insect pest resistance in sustainable agriculture. Nitrogen supply has a major impact on insect pest intensity as compared to low nitrogen doses and control, pest populations were high at high levels. Phosphorus (P) has an inconsistent role in resistance. Comprehensive nutrient management in sustainable agriculture offers cost-effective, eco-friendly disease control, reducing pesticide reliance. Potassium (K) enhances resistance to an optimal point, beyond which there is no further improvement. Proper nutrient management can make subsequent control measures more efficient and economical. Understanding the interplay of plant nutrition, insect herbivores, and community dynamics is essential. Balanced nutrient levels, especially potassium and phosphorus, indirectly strengthen plant resistance to various insect pests through biochemical, physical, and mechanical mechanisms. Strategies to enhance plant defense against phytophagous insects align with the demand for food and nutritional security. This review emphasizes the significance of comprehensive nutrient management in sustainable agriculture for disease and pest control while prioritizing food safety and environmental quality.

Keywords: [Plant nutrient, pest defense, herbivory, sucking pests, and insect nutrition]

1. INTRODUCTION

Insects and plants share ancient associations that date from the carboniferous era, some 300 million years ago. Evidence of insect damage preserved in fossilized plant parts indicates a diversity of types of phytophagy (plant-feeding) by insects [1]. Many insects rely on plants for food and shelter [2]. Plant and insect growth are interconnected in numerous ways [3]. Plant development is dependent on nutritional availability, whereas insect development is dependent on the quality of food supplied by its host plants [4]. The application of micro and macronutrients to crop plants may have an impact on the insect-plant relationship because nutrient-deficient plants are weak and sensitive to plant disease and insect pest assault [5]. Plants interact with a variety of species in nature and must integrate their responses to these varied community members. Plant-insect connections have accumulated significantly in recent decades [6]. Insect herbivore distributions and abundances of insect herbivores exhibit considerable variability over time and space across different spatial scales. The connection between plant biomass and insect herbivores can be readily explored, as both parameters can be linked to these patterns.

Plant nutrition is the study of the chemical elements and compounds necessary for plant growth and reproduction, plant metabolism and their external supply. In its absence, the plant is unable to complete a normal life cycle, or the element is part of some essential plant constituent or metabolites [7]. A plant nutrient is a chemical ingredient required by plants for growth and reproduction. Carbon, oxygen, and hydrogen are absorbed from the air, whereas other nutrients, like as nitrogen, are often received from the soil (exceptions include some parasitic or carnivorous plants). Plant nutrients are categorized according to mineral composition, nutrient content, and physiological activity. Apart from carbon, hydrogen, and oxygen, which plants obtain from carbon dioxide and water, 14 nutrients are recognized as essential for plant growth, including primary macronutrients (nitrogen, phosphorus, and potassium), secondary macronutrients (calcium, magnesium, and sulphur), and micronutrients (iron, manganese, zinc, copper, boron, molybdenum, chlorine, and nickel). The relative availability of various nutrients influences the growth and fitness of herbivores, whose biomass includes far higher quantities of components than plants [8]. Insects nutritional needs include carbohydrates, proteins, amino acids, fatty acids, minerals, and vitamins. Insects obtain nutrients from plants by feeding. Insect nutrition is the study of how nutrients and other elements in a diet interact with an organism's maintenance, growth, reproduction, health, and disease. Food intake, absorption, assimilation, biosynthesis, catabolism, and excretion are all included [9].

2. INSECT NUTRITION

Nutrition refers to the chemicals that an organism requires for growth, tissue maintenance, reproduction, and the energy required to perform these processes. Many of these compounds are consumed together with the food, but the insect itself produces others. Achieving adequate nutrition requires a complex combination of eating behaviour and post-infective food processing. Insects must consume adequate amounts of acceptable foods while avoiding toxic and nutrient excesses.

Table.1 Insect nutritional requirements and the dietary components [10].

Insect Nutrition		**Types of dietary components**
Amino acids	Amino acids are essential for the creation of proteins, which serve as structural elements, enzymes, transport and storage molecules, and receptor molecules E.g. Tyrosine (cuticular sclerotization), tryptophan (visual screening pigment)	Amino Acids Alanine, Lysine, Histidine, Glycine
Carbohydrates	Carbohydrates, including simple sugars, starch, and other polysaccharides, are important components of the diet for most insects. They are the usual respiratory fuel, can be converted to lipids and provide the carbon skeleton for the synthesis of various amino acids. In addition, insect cuticle characteristically contains the polysaccharide chitin.	Polysaccharides Starch, Glycogen (energy storage) Chitin, Cellulose (structural) Oligosaccharides Sucrose, Trehalose Simple Sugars Glucose, Galactose, Fructose
Lipids	Fatty acids, phospholipids, and sterols are components of cell membranes that also serve additional functions. As insects can synthesize many fatty acids and phospholipids, they do not normally require dietary elements, however, some insects do require polyunsaturated fatty acids (PUFAs) and all insects require sterols.	Fats (triglycerides) Oils, Waxes, Resins, Fatty Acids Cell membranes, Pheromones Steroids Hormones, Cholesterol
Vitamins	Vitamins are chemical compounds that are necessary in trace levels for long-term growth. Water-soluble vitamins are distinguished from lipid-soluble vitamins. In insect tissues, water-soluble vitamins have a much shorter half-life than lipid-soluble vitamins, which prefer to concentrate in lipid Stores.	Water soluble vitamins, beta-carotene, vitamin E, biotin, folicacid, etc. Lack of Vitamin C results in abortive ecdysis and death.
Minerals	Many insects use it to harden the cuticle of their mandibles.	Fe, Zn, Mn, etc.

3. NITROGEN EFFECT ON INSECT POPULATION GROWTH PARAMETERS

Nitrogen has a major impact on insect pest intensity as compared to low nitrogen doses and control, pest populations were high at high levels [11]. Nitrogen boosts individual insect performance, most likely due to changes in host plant chemistry caused by deposition. Nitrogenous fertilizer can generally improve herbivore feeding preference, food consumption, survival, growth, reproduction, and population density by modifying nutritional levels in plant tissues and significantly lowering host tolerance to insect herbivores [11]. Nitrogen fertilizer can increase herbivore food consumption, survival, growth, reproduction, and population density [12]. Nitrogen is an abiotic element that can influence crop plant volatile emissions and, as a result, insect behaviour. Excess nitrogen causes maturation to be delayed, encourages vegetative tendencies, and reduces yields [13].

3.1. What is the role of nitrogen in insects?

Nitrogen is a necessary ingredient for insects, as it is used to form cells, tissues, and living molecules. In general, insects obtain nitrogen from their feed to maintain their internal nitrogen balance. However, for many insects, particularly herbivores, living in low-nitrogen niches, the low content of total available nitrogen and an uneven supply of essential amino acids (EAAs) in diets severely limit their growth and development.

Table 2. Nitrogen effects on various insect pests

Insect Species	Effect	References
Thrips	Thrips attack new leaves of onion because those leaves have phloem only. Phloem tissues are rich in amino acids and amines. The phloem-feeding phytophagous insects, like thrips, prefer tissues which are rich in nitrogen	[14]
Mealy bug		
Planococcus citri	High N levels increased egg burdens, size, and developing time.	[15]
Planococcus ficus	Nitrogen increased survival	[16]
White fly		
Trialeurodesvaporariorum	Higher N levels increased eating, oviposition, distribution, immature survival, and the number of eggs and nymphs.	[17]
	With an increase in N, honeydew production increases while egg and nymph duration decreases.	[18]
Bemisia tabaci	Population growth is associated with a rise in N levels.	[19]
Aphid		
Aphis gossypii	N increased weight size, colouration, fertility, and dispersal to high N locations.	[20]
Brevicoryne brassicae	Increased nitrogen fertilization leads to a rise in population.	[21]
Lipaphjserysimi *Schizaphis graminum*	High N led to an increase in net reproduction rate, doubling time, and generation time.	[22]
Leafhoppers and plant hoppers		
Amrasca devastans	The highest N rate led to the highest population per leaf mean.	[23]
Empoasca decipiens	A rise in population accompanied by an increase in the rate of N	[24]
Nilaparvata lugens	At higher N, there is a larger population density.	[25]
Sogatella furcifera	A link exists between nitrogen levels and the occurrence of *S. furcifera*	[26]
Psylla		
Cacopsylla pyricola	Psylla populations were more abundant in the concentration of N treatment.	[27]
Borers and leaf folders		
Scripophaga incertulas and *Cnaphalocrocis medinalis*	With an increase in nitrogen content, the highest incidence was seen in the Punjab Bas-2 variety of rice. The incidence of leaf folder and stemborer increased as	[28]

	nitrogen levels increased.	
Moths Diamond back moth (*Plutella xylostella*)	The feeding preference of the cabbage plant has risen due to an excess of nitrogen.	[29]

3.2. Nitrogen-based management

Nitrogen's favourable effect on plant development overcomes the pest-controlling effects of not using it at all. However, dividing the treatment, using reasonable amounts, and adopting slow-release forms (such as sulphur-coated urea and urea super granules) can help to achieve the twin goal of increased yields and lower pest occurrence [30]. Thrips and whorl maggots, on the other hand, become less frequent when nitrogenous fertilizer is employed. The best nitrogen fertilizer regime in irrigated paddy fields is proposed to increase nitrogen use efficiency and prevent environmental contamination [31]. Proper potassium and nitrogen fertilizer application could help control insect herbivores like cotton aphids and plant growth at the seedling stage of a Bt-cotton field in Central China [32]. Jansson and Smilowitz [33] discovered a link between the population growth rate of the potato green peach aphid, *Myzus persicae* and the amounts of free amino acids in the leaves of nitrogen-fertilized plants

4. PHOSPHORUS

Phosphorus can undergo two reactions after being absorbed by plants. It can either stay inorganic phosphate (Pi) or be esterified to a carbon chain as a simple phosphate ester (e.g., sugar phosphate) or connected to another phosphate (e.g., ADP or ATP) [34]. When soil phosphorus supplies are adequate, nucleic acids (DNA, mRNA, tRNA, rRNA) account for 34% of total P content [35] the remaining P-containing fractions include lipids (21%), esters (23%), and inorganic phosphorus (21%). Due to these forms of P is available to insect herbivores [36], elemental P levels in plants correlate with P that insect herbivores can utilize. Phosphorus influences growth rate and population density. Phosphorus is essential for the growth of phytophagous insect populations since it is required for RNA synthesis. Potassium-induced changes in rice plants have a significant impact on insect-host interactions [37].Phosphorus limitation has been shown to influence insect survival, oviposition preference, growth rate, and population density [38]. Furthermore, phosphorus limitation has been widely observed in several aquatic invertebrates, particularly Daphnia, for whom low levels of ambient phosphorus frequently result in lower growth rates and competitive superiority [39]. As phosphorus is essential for nucleic acid synthesis (RNA) and consequently protein creation, its scarcity can have serious ramifications for cellular function and, ultimately on growth rate.

Table 3. Phosphorus effects on various insect pests

Insect	Effects	References
Bemisia tabaci	The application reduces the occurrence	[40].
Lipaphiserysimi	Use of P inhibited population growth	[41].
Macrosiphum	Beneficial influence on several aphid performance metrics	[42].
Empoasca dolichi	Lowered population density and caused damage	[43].
Clavigralla sp., Riptortus sp., Anoplocnemis., Mirperus sp. and Negara sp.	Increased P levels reduced population numbers and damage	[44].
Nilaparvata lugens	Phosphorus fertilization significantly increased population growth	[45].

5. POTASSIUM

Potassium is also required for the performance of numerous plant enzyme functions, and it affects the metabolite pattern of higher plants, resulting in metabolite concentration changes. The synthesis of high-molecular-weight compounds (such as proteins, starches, and cellulose) was significantly boosted in a K-sufficient plant, lowering the amounts of low-molecular-weight compounds (such as soluble sugars, organic acids, amino acids, and amides) in plant tissues [46]. Due to low-molecular-weight chemicals are critical for the development of infections and insect infestations, reduced quantities make K-sufficient plants less sensitive to disease and pest attacks. Adequate K raises phenol concentrations, which are important in plant resilience [47]. The role of potassium in reducing crop damage caused by insects is complicated. Potassium plays a crucial physiological role, including the development of insect pest resistance. Adequate quantities of K have been shown to significantly reduce the occurrence of insect damage. Plants with plenty of nitrogen but not enough potassium have soft tissue and limited resilience to sucking and chewing pests [48].

Adequate potassium levels in plants reduce carbohydrate accumulation, which reduces the possibility of attracting insect pests, but tissue yellowing symptoms of potassium deficiency act as a signal to attract aphids [49]. High levels of potassium, on the other hand, can improve secondary chemical metabolism, limit glucose accumulation, eliminate certain amino acids, raise the silica content of leaves, and protect plants from insect pests [50]. A sufficient potassium supply tends to harden plant structures, including aspects such as a thicker cuticle, a thicker outer wall of the epidermis, thicker cell walls, enhanced development of sclerenchymatous tissues, increased lignification and silicification, and thicker and harder stems. This hardening of plant structures is thought to improve mechanical resistance to insect feeding, particularly sucking insects.

5.1. Management with potassium

Enough potassium hardens plant structures by hardening cell walls, resulting in thicker and harder stems and leaves. This hardening of plant structures improves mechanical resistance to insect feeding, particularly sucking insects like aphids. Potassium also inhibits the growth and development of sucking pests. Higher plant potassium levels reduced aphid occurrence, population levels, population growth rate, and net reproductive rate [51].The presence of sufficient potassium also promotes the production of defensive compounds (such as phenols) which are an important component in plant pest resistance. An adequate potassium concentration within the plant decreases the internal competition with various pests and pathogens for resources. This results in more resources available for hardening cell walls and tissues to better resist penetration of pathogens and insect pests, and to repair any damaged tissue [52]. Air-borne pathogens are more rapidly shut out from stomatal invasion when adequate potassium is present.

Table 4. Potassium effects on various insect pests

Insect	Effects	References
Bemisia tabaci	Plants fertilized with K have a moderate population.	[53].
Lipaphiserysimi	K application inhibited population growth	[54].
Myzus persicae	Higher doses resulted in the fewest aphids per plant	[55].
Nilaparvata lugens	The use of high K reduced population build-up and the dry weight of BPH.	[56].

6. INFLUENCE OF SECONDARY MACRONUTRIENTS AND MICRONUTRIENTS

Pest populations are also reduced by secondary macronutrients and micronutrients such as calcium, zinc, and sulphur. Silicon, a mineral element, is implicated in plant resistance to insect pest damage [57]. Cropping practices have removed measurable amounts of these nutrients from the soil over time. As a result, secondary macronutrient deficits are becoming a more significant concern in intensive crop production systems, particularly in soils that have only been fertilized with primary macronutrients. Aside from core macronutrients, secondary macronutrients and micronutrients have an impact on pest populations.

Calcium (Ca) in the plant is utilized to generate calcium pectate, which controls the strength of the cell walls and their resistance to insect and disease attacks. Calcium oxalate is the most abundant insoluble mineral in plants and is present in a wide range of plant families. Plant calcium oxalate crystals can take the form of irregular rectangles, spiky balls, or needles [58]. The intimidating aspect of these crystals has sparked suspicion that they could be used to control pests by deterring eating insects.

Manganese (Mn) is essential for photosynthesis, nitrogen metabolism, lignin formation, root development, and numerous enzyme systems to function. In plants, magnesium also serves as a phosphorus transporter. It is required for cell division and protein synthesis. Phosphorus absorption would be impossible without magnesium, and vice versa [59]. As a result, magnesium is required for phosphate metabolism, plant respiration, and the activation of several enzyme systems.

Silicon improves plant resistance and lowers plant damage caused by diseases, insect pests, and non-insect pests by mediating and up regulating both constitutive (i.e., regardless of insect presence) and induced (*i.e*., in response to insect attack) resistance pathways. A variety of examples show that Si can improve the resistance of both monocotyledonous crops and numerous dicot plant species to insect pests from the Lepidoptera [63], Hemipter(Homoptera}, Diptera, Thysanoptera, and Coleoptera feeding guilds, as well as non-insect pests [64 and 65]. Because silica makes plant tissues difficult for insects to chew, penetrate, and digest, Si deposition patterns inside plant tissues led to the concept of mechanical or physical barriers to insect feeding. Furthermore, the beneficial activities of silica in plant physiology, regulation of defense-related enzymes, plant hormone signalling, and change of plant volatile blends shed light on Si's link with biochemical/molecular defense systems (Figure 1). Chewing insects are more vulnerable to Si physical barriers than phloem feeders, which may be able to evade the phytoliths, but we cannot rule out the potential that plant tissue injury caused by feeding itself may initiate the battery of Si-induced plant responses [66].

Table 5. Secondary macronutrients and micronutrients

Nutrient	Effect	References
Sulphur	Greater reaction with lower frequency	[60].
Zinc	Zn content in foliage demonstrated a negative connection.	[61].
Micronutrients	Discovered to not affect the proliferation of the whitefly, *B. tabaci*, in cotton crops.	[62].

Figure 1. Plant resistance to insect pests is mediated by silicon

6.1 Nutrition management

Silicon (Si) strengthens plant tolerance and protects against abiotic stresses, as well as reduces the incidence of insects and diseases. It also results in increased yield and production. Due to reduction in insect performance and plant damage, the use of silicon fertilizer is a feasible strategy and alternative management option to chemical control insect pests. Silicon strengthens plant defense against a variety of insect pests, including borers and sap-feeding insects [67].

Table 6. Plant resistance mechanisms and defensive responses mediated by silicon

Crop	Insect	Resistance Mechanism	References
Rice	Rice leaf folder *Cnaphalocrocis medinalis*	Reduced insect food quality and efficiency of food processing; stimulating defense-related enzymes	[68].
	Asiatic rice borer *Chilo suppressalis Walker*	Early instar larvae impeded stalk penetration and lengthened penetration duration	[69].
	Brown plant hopper *Nilaparvata lugens Stål*.	Physical barriers and chemical defenses that are induced	[70].
Maize	Corn Armyworm	Biological parameters (fecundity of	[71].

	Spodoptera fruiter	females) were affected	
Sunflower	Sunflower caterpillar *Chlosyne lacinia saundersii*	Feeding habit was influenced by leaf palatability	[72].
Wheat	Green bug *Schizaphis graminum Romani*	Induced barriers that impact preference and inhibit population growth	[73].
Sugarcane	Greyback cane grub *Ermelinda altohyrtin*	Lignin buildup has increased	[74].

7. THE EFFECTS OF FERTILIZATION ON PLANT RESISTANCE TO INSECT PESTS

Plant resistance to insect pests has been proven to vary with plant age or growth stage [75]. This implies that resistance is closely related to plant physiology, and hence any event that affects plant physiology may result in changes in resistance to insect pests. Fertilization has been found to influence all three types of Painters [76] resistance: preference, antibiosis, and tolerance. Many pests species success in utilizing the host is influenced by the obvious morphological reactions of crops to fertilizers, such as changes in growth rates, hastened or delayed maturity, size of plant components, and thickness and hardness of epicuticle.

Table 7 The effects of fertilization on plant resistance to insect pests

Insect	Effect of fertilizers	References
Boll weevil larvae	Three times as many boll weevil larvae (*Anthonomus grandis*) on cotton (*Gossypium hirsutum*) receiving heavy applications of fertilizers compared to unfertilized checks.	[77].
Corn earworm (*Heliothis zea*)	Nitrogen fertilizer increased husk extension and tightness of husks on sweet corn (*Zea mays*) influencing corn earworm (*Heliothis zea*) infestation levels	[78].

7.1. Utilisation of fertilisers for management

Plant resistance to several insect pests has been documented to be influenced indirectly by fertilization practices operating through changes in crop nutrient content. Excessive and/or incorrect application of inorganic fertilizers might result in nutritional imbalances and decreased insect resistance [78]. Proper fertilization is required to provide the plants with some level of pest resistance. Plants primary pest defense qualities, such as physical and biochemical properties, can be improved through balanced fertilization using plant nutrients. When soil amendments such as poultry manure and inorganic fertilizers are applied to restore or increase fertility, pest control measures such as the use of chemical insecticides and other pest management options should be implemented to mitigate the effects of insect pest infestation on crop productivity. Rising fertilizer availability has significantly impacted the global nutrient cycle, causing changes in terrestrial and aquatic systems [79].

7.2. Plant defense systems are strengthened by nutrients

Plant health affects both the external and internal development of plant defense mechanisms. Plants first line of defense against insects and disease is mechanical barriers (e.g., cell walls, bark, etc.). These barriers would be weak, misshapen, and inefficient without nutrients like calcium, boron, zinc, and silicon. Systemic acquired resistance (SAR) is caused by potassium and manganese, which aid in the release of defense compounds that help inoculate plants against attacks [80].

7.3. Effects of elevated nutrient levels

Elevated nutrient levels can be an invitation for insects to move in. Plants with excessive nitrogen levels, for example, can attract mites and aphids. High nitrogen levels also promote leafy, new growth. While this may seem like a good thing at first, the new foliage is often weak and straggly, making it the perfect target for insects [81]. Effects of phosphorous and nitrogen levels in impatiens on Western flower thrips (WFT) populations. Researchers found that elevated phosphorus levels contributed to the accelerated growth of WFT populations [82].

Tips for managing nutrient levels in plants to reduce the risk of insect infestation:

a. Use a balanced fertilizer that contains all the essential nutrients that your plants need.
b. Avoid over-fertilizing. Too much fertilizer can make plants more susceptible to pests and diseases.
c. Test your soil regularly to determine the nutrient levels. This will help you to avoid over-fertilizing or under-fertilizing.

d. Choose plants that are well-suited to your climate and soil conditions. Plants that are stressed due to environmental factors are more susceptible to pests and diseases.
e. Monitor your plants regularly for signs of insect infestation. If you see any pests, take steps to control them immediately.

7.4. Effects of low nutrient levels

Nutrient deficiencies can inhibit the production of a plant's biochemical defense compounds. This is because nutrients are essential for the synthesis of many of the compounds that plants use to defend themselves against pests and diseases. For example, potassium is necessary to produce flavonoids, which are a class of secondary metabolites that have antifungal and antibacterial properties. Boron is essential to produce phenols, which are another class of secondary metabolites that can deter pests and diseases. Manganese is necessary to produce lignin, which is a structural component of plant cell walls that can make it more difficult for pests and diseases to penetrate. Silicon influences the release of defensive compounds, such as phytoalexins, which are antimicrobial compounds that plants produce in response to infection [84 and 85].

In addition to the nutrients mentioned above, other nutrients that can be important for plant defense include nitrogen, phosphorus, sulphur, and zinc. Nitrogen is essential to produce proteins, which are involved in many different defense mechanisms. Phosphorus is essential to produce ATP, which is the energy currency of the cell and is needed for all metabolic processes, including defense responses. Sulphur is essential to produce glycosylates, which are a class of secondary metabolites that can deter pests and diseases. Zinc is essential to produce enzymes that are involved in defense responses. Overall, it is important to maintain adequate nutrient levels in plants to ensure that they have the resources they need to defend themselves against pests and diseases.

7.6. Keep plant nutrition balanced

Maintaining balanced plant nutrition is an effective preventive technique for insect control on plants, especially when paired with other integrated pest management practices. An effective integrated pest management strategy should include a balanced nutrition programme that is tailored to the crop type, plant lifespan, and soil type.

8. CONCLUSION

A nutrient-focused approach is essential in disease and pest management for sustainable agriculture. When nutrients are applied appropriately, they can reduce crop disease incidence by enhancing plant tolerance or resistance mechanisms, particularly when addressing nutrient deficiencies. However, it is important to note that excessive nutrient levels can sometimes worsen diseases due to toxicity or interactions with deficiencies. Balanced nutrient management is not only cost-effective but also environmentally friendly, potentially reducing the need for pesticides. Achieving this balance is key in modern agriculture to ensure both sufficient yield and effective pest management. Nitrogen fertilization plays a significant role in influencing insect populations and their distribution. Optimizing fertilizer use is crucial to maintaining a harmonious equilibrium, maximizing yields, and managing pests effectively. Herbivore populations are known to respond to changes in plant nutrition, further emphasizing the importance of optimizing chemical fertilizer use and implementing strategies like silicon-induced plant resistance. These approaches are essential in maintaining low pest populations and reducing yield losses in sustainable agriculture. In summary, adopting a nutrient-focused approach to disease and pest management is indispensable for sustainable agriculture, where the careful management of nutrients not only enhances plant health and disease resistance but also contributes to effective pest control and reduced environmental impact.

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