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REVIEW OF MODERN METHODS FOR OPTIMIZING APPLE MINERAL NUTRITION TO INCREASE YIELD AND FRUIT PRESERVATION

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Abstract. Achieving sustainable fruit production and ensuring quality preservation are paramount in modern apple orchards. This review delves into contemporary methods designed to optimize mineral nutrition, aiming to bolster both yield and fruit preservation. Various strategies for enhancing apple orchard management are examined, with a focus on maximizing the efficacy of mineral fertilizers, maintaining balanced nutrition, and understanding the critical role of key nutrients such as nitrogen, phosphorus, potassium, calcium, and boron. The review underscores the importance of comprehending plant nutrient requirements across different growth stages and phenological phases to attain sustainable, high-quality fruit production. Furthermore, it emphasizes the necessity of continuous diagnostic assessments to tailor mineral nutrition practices to the specific needs of apple orchards, ensuring optimal performance and economic viability.

Key words: apple orchards, mineral nutrition, yield enhancement, fruit preservation, sustainable agriculture, nutrient management, orchard management.

INTRODUCTION:

Sustainable fruit production in apple orchards relies heavily on optimal mineral nutrition to ensure both high yields and fruit preservation. Achieving stable fruit production and maximizing yield in intensive apple orchards necessitates an intricate understanding of the plant's nutrient requirements throughout various growth stages and phenological phases [1] The significance of mineral nutrition in sustaining fruit quality and quantity cannot be overstated, as it directly influences factors such as fruit firmness, storability, and overall marketability [2].

This review aims to explore contemporary methods for optimizing mineral nutrition in apple trees to enhance both yield and fruit preservation. By examining current research and practices, this article seeks to provide insights into effective strategies for managing plant nutrient requirements, diagnosing deficiencies, and implementing balanced fertilization approaches [3]. Additionally, it will highlight the importance of diagnostic assessments in orchard management and the role of nutrient management in sustainable agriculture practices [4].

Through a comprehensive analysis of the literature, this review intends to offer valuable perspectives on enhancing apple orchard productivity while ensuring fruit quality and longevity. By addressing key challenges and opportunities in mineral nutrition optimization, this review aims to contribute to the advancement of sustainable fruit production practices in apple orchards [5].

LITERATURE REVIEW

The literature on optimizing mineral nutrition for apple trees to enhance yield and fruit quality is extensive and multifaceted. A considerable body of research has explored various aspects of mineral uptake, nutrient balance, and their implications for orchard productivity. [6] Early studies by Weetman [7] and

Mitcherlih [8], Panfilov and Sokolov [9], and Thomas [10] laid the groundwork for understanding the importance of soil and foliar analysis in determining fertilizer requirements for fruit trees. Subsequent works by Boynton [11], Semenyuk [12] and Neilsen [13] delved deeper into the relationship between soil nutrient levels, leaf nutrient concentrations, and orchard performance.

Further advancements in diagnostic techniques have been made in recent decades, with researchers like Trunov and Kuzin [14] emphasizing the role of plant and soil diagnostics in fertilizer management. The use of optical characteristics such as chlorophyll fluorescence Demotes-Mainard et al. [15] and leaf reflectance coefficients Foster et al. [16] has emerged as valuable tools for non-destructive assessment of nutrient status in apple trees.

Regarding specific nutrients, calcium has garnered significant attention due to its pivotal role in fruit firmness and post-harvest storability. Studies by Faust [17] Conway [18], Chuntanaparb [19], Hanger [20] and Bramlage et al. [21, 22] underscored the importance of adequate calcium supply in reducing post-harvest disorders and enhancing fruit quality. Similarly, investigations into the effects of nitrogen, phosphorus, and potassium fertilization on fruit characteristics have yielded valuable insights Neilsen et al., Webster and Lidster; Fallahi et al. [23-25].

However, challenges remain in optimizing fertilizer practices to achieve both high yields and fruit quality. The interactions among various nutrients, as well as their uptake dynamics under different environmental conditions, necessitate a holistic approach to orchard management. Future research efforts should focus on refining diagnostic tools, elucidating nutrient interactions, and developing targeted fertilizer strategies tailored to specific orchard requirements.

Continued advancements in soil science and plant nutrition have deepened our understanding of the complexities of managing mineral nutrition in apple orchards. Studies by Taylor and Gourban [26] highlighted the importance of considering root activity and soil nutrient dynamics in nutrient management strategies. Furthermore, investigations into the role of non-root fertilization techniques, such as foliar and fertigation applications, have provided insights into enhancing nutrient uptake efficiency and fruit quality Johnson and Yogoratham, Fallahi et al. [27].

The influence of individual nutrients on fruit quality extends beyond calcium, with nitrogen, phosphorus, and potassium playing crucial roles. Nitrogen, in particular, has been extensively studied due to its multifaceted effects on tree growth, yield, and fruit composition. Research by Martin et al. [28] and Neilsen et al. [23] demonstrated the delicate balance required to optimize nitrogen supply while minimizing the risk of physiological disorders such as bitter pit.

Phosphorus, though often overshadowed by nitrogen and potassium, remains a vital nutrient for orchard productivity. Studies by Boyton and Oberly [29] and Cripps [30] emphasized the significance of phosphorus in sustaining tree vigor and enhancing fruit quality, especially under conditions of soil depletion. Additionally, investigations into the role of micronutrients, such as boron, magnesium, and zinc, have shed light on their contributions to fruit development and storability Faust and Shear [31]; Bramlage et al. [32].

Despite these advancements, gaps in knowledge persist, particularly regarding the interaction between nutrient management practices and environmental factors. The dynamic nature of soil-plant interactions necessitates ongoing research to refine fertilization strategies and mitigate nutrient imbalances. Furthermore, the integration of precision agriculture technologies and data-driven approaches holds promise for optimizing nutrient applications based on real-time soil and plant monitoring [33].

The literature provides a rich tapestry of research findings and insights into optimizing mineral nutrition in apple orchards. Building upon this foundation, future research endeavors should address knowledge gaps, refine management practices, and harness innovative technologies to sustainably enhance orchard productivity and fruit quality.

METHODS FOR NUTRIENT ANALYSIS

In the pursuit of optimal mineral nutrition management in apple orchards, the accurate analysis of nutrient levels in soil, leaves, and fruits is fundamental. Several methods are employed for nutrient analysis, each offering unique advantages and applications tailored to specific research objectives and practical considerations.

Soil Nutrient Analysis

Soil nutrient analysis involves assessing the chemical composition of the soil to determine nutrient availability and potential deficiencies or excesses. Common techniques include soil sampling, extraction methods such as Mehlich-3 [34] or ammonium bicarbonate-diethylenetriaminepentaacetic acid (AB-DTPA) [35], and analysis of extracted solutions using spectrophotometry or ion chromatography [36]. These methods provide valuable insights into soil nutrient status, pH levels, and cation exchange capacity, guiding fertilizer recommendations and soil management practices.

Leaf Nutrient Analysis

Leaf nutrient analysis serves as a vital tool for diagnosing nutrient deficiencies or imbalances in apple trees during the growing season. Leaf tissue samples are collected at specific growth stages and analyzed for nutrient concentrations using techniques such as dry ashing, wet digestion [37], or inductively coupled plasma (ICP) spectroscopy [38]. By comparing nutrient levels against established sufficiency ranges, growers can identify nutrient deficiencies early and adjust fertilizer applications accordingly to optimize tree nutrition and productivity.

Fruit Nutrient Analysis

Fruit nutrient analysis is essential for evaluating the nutritional quality of apple yields and assessing the impact of mineral nutrition management practices on fruit composition. Fruit samples are collected at maturity and analyzed for nutrient content using methods such as wet digestion, extraction [39], and atomic absorption spectroscopy. This analysis provides valuable information on key nutrients such as calcium, potassium, and magnesium, influencing fruit quality attributes such as firmness, flavor, and storability [40].

Advanced Techniques

Advances in analytical instrumentation and techniques, such as X-ray fluorescence (XRF) [41] spectroscopy and near-infrared (NIR) spectroscopy, offer rapid and non-destructive methods for nutrient analysis in soils, leaves, and fruits. These techniques enable high-throughput analysis with minimal sample preparation, facilitating timely decision-making in orchard management and precision agriculture applications [42].

By employing a combination of traditional and advanced analytical methods, researchers and growers can effectively monitor and manage mineral nutrition in apple orchards, optimizing tree health, yield potential, and fruit quality [43].

Based on the research of Ahad S. and colleagues, it is possible to determine the removal of nutrients from the soil during harvest depending on the yield. data are given in table 1 [44].

Table 1 - Fruit nutrient removal (tones/ hectare) at harvest in relation to yield

Yield (tones/ hectare)	N	P	K	Ca	Mg	S
2,5	43,0	11,0	138,5	9,0	7,0	3.5
4	70,3	17.6	221,3	14,1	11,4	5.0
5,5	94,6	24.2	304,2	19,3	15,4	6.5
7	120,4	33.9	387.0	24,5	19,6	8.0
8	137,0	38.7	442,7	28,3	22,4	10.0
9,5	163,4	46.0	525,5	33,1	26,6	11.5

OPTIMIZATION STRATEGIES FOR MINERAL NUTRITION IN APPLE ORCHARDS

Optimizing mineral nutrition is paramount for achieving high yields and fruit quality in apple orchards. This section delves into various strategies, encompassing fertilization techniques, irrigation management, and soil amendments, aimed at enhancing mineral nutrition in apple trees [45]. Tree nutrient requirements in relation to yield presented in table 2 [44].

Table 2. Tree nutrient requirements (tones/ hectare) in relation to yield

Yield (tones/ hectare)	N	P	K	Ca	Mg	S
2,5	120.4	20.2	219.1	86.7	26.7	9.8
4	192.7	32.3	350.5	138.6	42.7	15.7
5,5	265.0	44.4	482,0	190.6	58.7	21.6
7	337.2	56.5	613,5	242.6	74.8	27.5
8,5	409.5	68.6	744.9	294.6	90.8	33.4

Fertilization Techniques

Fertilization techniques play a pivotal role in optimizing mineral nutrition management in apple orchards, offering precise control over nutrient application and uptake by trees [46]. Several key fertilization techniques are employed, each with distinct advantages and considerations:

Conventional Fertilization: Conventional fertilization involves the application of granular or liquid fertilizers directly to the soil surface or through irrigation systems. Granular fertilizers, such as ammonium nitrate or triple superphosphate, are commonly broadcasted or banded in orchard rows, ensuring uniform nutrient distribution and uptake by tree roots. Liquid fertilizers, including soluble nitrogen, phosphorus, and potassium formulations, are applied via fertigation systems, delivering nutrients directly to the root zone with irrigation water. These methods allow for precise nutrient management, tailored to the specific needs of apple trees at different growth stages [47].

Slow-Release Fertilizers: Slow-release fertilizers offer a controlled-release mechanism for supplying nutrients to apple trees over an extended period. These fertilizers, often in granular or coated pellet form, gradually release nutrients in response to soil moisture and microbial activity, reducing the risk of nutrient leaching and runoff. Common slow-release formulations include polymer-coated urea for nitrogen and controlled-release phosphorus compounds. By providing a steady supply of nutrients, slow-release fertilizers promote sustained tree growth and minimize nutrient losses, particularly in sandy or low-fertility soils [48].

Organic Fertilization: Organic fertilization involves the application of natural or organic materials, such as compost, manure, or bio-based amendments, to enhance soil fertility and nutrient availability in apple orchards. Organic fertilizers contribute to soil organic matter content, improve soil structure, and stimulate microbial activity, leading to gradual nutrient release and improved nutrient retention. Additionally, organic fertilizers contain micronutrients and beneficial organic compounds that support overall tree health and resilience to environmental stressors. Incorporating organic fertilization practices into orchard management promotes sustainable nutrient management and enhances long-term soil health and productivity [49].

Precision Fertilization: Precision fertilization techniques leverage advanced technologies, such as global positioning systems (GPS), remote sensing, and soil mapping, to tailor nutrient applications to specific orchard zones based on soil fertility, tree vigor, and historical yield data. Variable-rate fertilization systems allow growers to adjust fertilizer rates and application timings according to spatial variability within the orchard, optimizing nutrient use efficiency and minimizing over-application. By targeting fertilizer inputs to areas of greatest need, precision fertilization enhances nutrient uptake by apple trees, reduces fertilizer wastage, and improves overall orchard productivity and profitability [50].

Incorporating a combination of fertilization techniques, including conventional, slow-release, organic, and precision methods, enables growers to optimize mineral nutrition management in apple orchards, ensuring sustained tree health, high yield potential, and premium fruit quality [51].

Irrigation Management.

Effective irrigation management plays a crucial role in optimizing mineral nutrition in apple orchards, influencing nutrient availability, uptake, and distribution within the soil-plant-water system. Various irrigation techniques are employed to ensure adequate water supply while minimizing nutrient leaching and runoff, thereby maximizing nutrient utilization efficiency and orchard productivity [46]:

Drip Irrigation: Drip irrigation systems deliver water directly to the root zone of apple trees through a network of low-pressure emitters or tubing, minimizing water loss through evaporation and surface runoff. By precisely controlling water application rates and timing, drip irrigation enables growers to tailor irrigation schedules to meet the specific water requirements of apple trees at different growth stages. Additionally, drip irrigation can be integrated with fertigation systems to deliver nutrients alongside irrigation water, enhancing nutrient uptake efficiency and minimizing nutrient losses [52].

Sprinkler Irrigation: Sprinkler irrigation involves the overhead application of water through sprinkler heads or nozzles, distributing water uniformly across the orchard canopy. While less water-efficient than drip irrigation, sprinkler systems are well-suited for cooling apple trees during periods of high temperature and reducing heat stress. Furthermore, sprinkler irrigation can facilitate the application of foliar fertilizers and soil amendments, enhancing nutrient availability and uptake by apple trees [53].

Subsurface Drip Irrigation: Subsurface drip irrigation systems deliver water directly to the root zone below the soil surface, minimizing water evaporation and soil surface wetting. By maintaining soil moisture levels near the root zone, subsurface drip irrigation promotes deep root development and enhances nutrient uptake by apple trees. Additionally, subsurface drip systems reduce weed growth and soil compaction, improving overall orchard health and productivity [54].

Soil Moisture Monitoring: Soil moisture monitoring technologies, such as tensiometers, capacitance probes, and neutron probes, allow growers to assess soil moisture levels in real time and adjust irrigation schedules accordingly. By optimizing irrigation timing and duration based on actual soil moisture data, growers can prevent both water stress and excess soil moisture, optimizing nutrient availability and uptake by apple trees. Furthermore, soil moisture monitoring facilitates the implementation of deficit irrigation strategies, where water is intentionally withheld during non-critical growth stages to promote root growth and nutrient absorption [55].

By implementing appropriate irrigation management practices, apple growers can optimize mineral nutrition uptake by trees, enhance orchard productivity, and improve fruit quality, ultimately contributing to sustainable orchard management and profitability [52].

Soil Amendments

Soil amendments play a critical role in optimizing mineral nutrition in apple orchards by enhancing soil fertility, structure, and nutrient availability [56]. Various soil amendment techniques are employed to address soil deficiencies, improve nutrient retention, and promote healthy root growth, thereby maximizing nutrient uptake by apple trees:

Organic Matter Addition: Incorporating organic matter, such as compost, manure, or cover crops, into orchard soils improves soil structure, water retention, and microbial activity. Organic matter serves as a source of essential nutrients, enhances soil biodiversity, and promotes the decomposition of organic residues, releasing nutrients in plant-available forms. By increasing soil organic matter content, growers can improve nutrient cycling, reduce nutrient leaching, and enhance overall soil fertility, supporting optimal mineral nutrition uptake by apple trees [57].

Liming: Liming involves the application of agricultural lime (calcium carbonate) to acidic soils to raise soil pH levels and reduce soil acidity. Maintaining appropriate soil pH levels is essential for optimizing nutrient availability and uptake by apple trees, as soil pH influences nutrient solubility, microbial activity, and root growth. By correcting soil acidity through liming, growers can improve the availability of essential nutrients, such as calcium, phosphorus, and magnesium, and mitigate nutrient deficiencies inapple orchards [58].

Gypsum Application: Gypsum (calcium sulfate) application is utilized to improve soil structure, reduce soil compaction, and enhance water infiltration and drainage in apple orchards. Gypsum supplies calcium and sulfur, essential nutrients for apple tree growth and development, while also improving soil aeration and root penetration. Additionally, gypsum can mitigate soil salinity issues by promoting the leaching of excess salts from the root zone, thereby improving nutrient uptake efficiency and reducing the risk of salt-induced nutrient imbalances [59].

Micronutrient Amendments: Micronutrient deficiencies, such as boron, zinc, iron, and manganese deficiencies, can negatively impact apple tree growth, yield, and fruit quality. Soil amendments containing micronutrients are applied to correct nutrient imbalances and ensure optimal mineral nutrition uptake by apple trees. Chelated micronutrient fertilizers or foliar sprays are commonly used to supply deficient micronutrients directly to apple trees, bypassing soil limitations and promoting rapid nutrient absorption and utilization [60].

By incorporating appropriate soil amendment practices into orchard management strategies, growers can improve soil health, nutrient availability, and mineral nutrition uptake by apple trees, ultimately enhancing orchard productivity and fruit quality.

DIAGNOSTIC TOOLS AND MONITORING

Diagnostic tools and monitoring techniques are essential components of nutrient management strategies in apple orchards, enabling growers to identify and address nutrient deficiencies or imbalances promptly [61]. By utilizing a combination of visual observations, soil and tissue analysis, and advanced monitoring technologies, growers can accurately assess the nutritional status of apple trees and implement targeted corrective measures.

Visual Observations: Visual symptoms exhibited by apple trees, such as leaf discoloration, stunted growth, leaf deformities, or fruit abnormalities, can provide initial indications of nutrient deficiencies or imbalances. Growers conduct regular visual inspections of orchards to identify potential nutrient stress symptoms and monitor changes in tree health and vigor throughout the growing season. Visual observations serve as a preliminary diagnostic tool, prompting further investigation through more precise analytical methods [62].

Soil Analysis: Soil analysis involves the collection and testing of soil samples from various locations within the orchard to assess soil nutrient levels, pH, and other physicochemical properties. Soil testing provides valuable insights into soil fertility status, nutrient availability, and potential nutrient limitations affecting apple tree growth and development. By analyzing soil nutrient concentrations and pH levels, growers can make informed decisions regarding fertilizer application rates, timing, and formulations to address specific nutrient deficiencies or imbalances [63].

Tissue Analysis: Tissue analysis entails the sampling and laboratory analysis of plant tissues, such as leaves or fruit, to quantify nutrient concentrations and identify nutrient deficiencies or excesses. Leaf tissue analysis is particularly useful for assessing the nutritional status of apple trees during the growing season, as it provides real-time data on nutrient uptake and utilization by plants. By analyzing nutrient levels in plant tissues, growers can diagnose nutrient deficiencies, monitor nutrient imbalances, and adjust fertilizer programs accordingly to optimize mineral nutrition uptake and tree productivity. Optimal level of nutrients in apple leaves presented in table 3.

Table 3 - Optimal level of nutrients in apple leaves

Nutrient	Concentration
Nitrogen	2.2-2.6%
Phosphorous	0.13-0.33%
Potassium	1.35-1.85%
Calcium	1.3-2%
Magnesium	0.35-0.5%
Sulfur	0.18-0.25%
Boron	25-50 ppm
Zinc	25-50 ppm
Copper	7-12 ppm
Iron	50+ ppm

Source- Ahad S. et al 2018 [44]

Advanced Monitoring Technologies: Advanced monitoring technologies, such as sap analysis, canopy sensors, or drone-based imaging, offer innovative approaches to monitor apple tree nutrition and physiological status non-invasively. Sap analysis involves measuring nutrient concentrations in tree sap collected from xylem or phloem tissues, providing insights into nutrient transport and assimilation processes within the plant. Canopy sensors utilize spectral data to assess canopy vigor, chlorophyll content, and nutrient status, enabling growers to optimize fertilizer applications based on real-time crop responses. Drone-based imaging techniques offer high-resolution aerial imagery for mapping orchard health, identifying nutrient stress zones, and implementing targeted nutrient management interventions [64].

By integrating diagnostic tools and monitoring techniques into orchard management practices, growers can proactively identify nutrient deficiencies or imbalances in apple trees and implement timely corrective measures to optimize mineral nutrition uptake, enhance tree health and vigor, and maximize orchard productivity and fruit quality.

CASE STUDIES AND EXAMPLES

In this section, we present real-world examples and case studies that showcase successful approaches to optimizing mineral nutrition in apple orchards. These examples highlight the implementation of various strategies, including fertilization techniques, irrigation management, soil amendments, and diagnostic tools, to improve apple tree health, productivity, and fruit quality.

Fertilization Techniques: A case study demonstrates the efficacy of precision fertilization techniques in addressing specific nutrient deficiencies identified through soil and tissue analysis. By customizing fertilizer formulations and application rates based on site-specific soil conditions and tree nutrient requirements, growers can achieve optimal nutrient uptake and utilization, resulting in improved tree vigor, fruit set and yield [65].

Irrigation Management: Another case study illustrates the importance of efficient irrigation management practices in optimizing apple tree nutrition and water use efficiency. By implementing drip irrigation systems or deficit irrigation strategies, growers can deliver water and nutrients directly to the root zone, minimizing nutrient leaching and maximizing nutrient uptake by plants. Proper irrigation scheduling based on soil moisture monitoring and weather forecasts ensures optimal water and nutrient availability throughout the growing season, promoting healthy tree growth and fruit development. Recommended rates of NPK for Apple Trees presented in figure 1 [66].

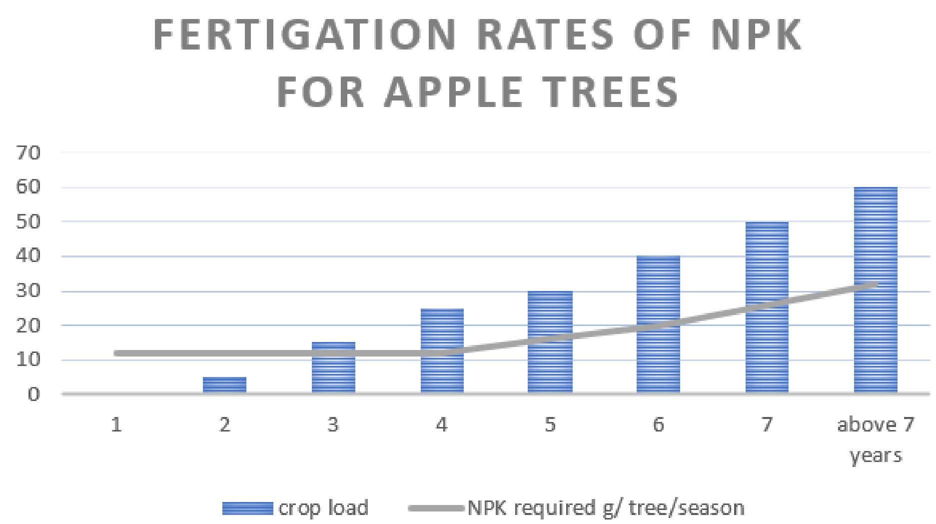

Figure 1 - Fertigation rates of NPK for Apple Trees

Soil Amendments: A third case study highlights the role of soil amendments, such as compost, biochar, or gypsum, in improving soil structure, fertility, and nutrient availability for apple trees. By incorporating organic amendments or soil conditioners into orchard soils, growers can enhance nutrient retention, microbial activity, and root development, leading to improved nutrient uptake and tree performance. Soil amendment applications tailored to specific soil deficiencies or constraints can mitigate nutrient imbalances and enhance overall orchard sustainability and resilience [67].

Diagnostic Tools and Monitoring: Additional case studies demonstrate the practical application of diagnostic tools and monitoring technologies in diagnosing nutrient deficiencies or imbalances and guiding targeted nutrient management interventions. By routinely conducting soil and tissue analyses, utilizing canopy sensors, or employing drone-based imaging, growers can accurately assess orchard nutrient status, identify problem areas, and implement corrective actions to optimize mineral nutrition uptake and tree health [68].

These case studies underscore the importance of adopting integrated nutrient management approaches tailored to site-specific conditions and production goals to achieve sustainable and profitable apple orchard management. By learning from successful examples and applying proven strategies, growers can enhance mineral nutrition management practices, improve orchard productivity and fruit quality, and ensure long-term profitability and environmental stewardship.

CHALLENGES AND FUTURE DIRECTIONS

This section critically examines the challenges and limitations inherent in current mineral nutrition management practices in apple orchards and identifies potential areas for future research and improvement.

1. *Nutrient Imbalance and Soil Degradation:* One of the primary challenges facing apple growers is the occurrence of nutrient imbalances and soil degradation, which can adversely affect tree health and productivity. Excessive fertilizer application or inadequate nutrient replenishment strategies may lead to nutrient leaching, soil acidification, or salinity problems, compromising long-term soil fertility and sustainability. Addressing these challenges requires a holistic approach that integrates soil health management, precision fertilization techniques, and sustainable soil conservation practices [69].

2. *Climate Change and Water Scarcity:* The increasing frequency and intensity of climate variability, coupled with water scarcity concerns, pose significant challenges to apple orchard management. Erratic weather patterns, prolonged droughts, or extreme temperature events can disrupt nutrient availability, water uptake, and overall tree performance, exacerbating nutrient stress and yield losses [70].

Developing resilient orchard management strategies that enhance water use efficiency, optimize irrigation scheduling, and mitigate climate-related risks is essential for adapting to changing environmental conditions and ensuring orchard sustainability [71].

3. *Technology Integration and Data Management:* While advancements in diagnostic tools and monitoring technologies offer valuable insights into orchard nutrient status and performance, their effective integration and data management present practical challenges for growers. Limited accessibility to affordable and user-friendly technologies, as well as the interpretation of complex data outputs, may hinder widespread adoption and utilization. Investing in user-friendly decision support systems, digital platforms, and training programs can empower growers to make informed nutrient management decisions and optimize orchard productivity [72].

4. *Regulatory Compliance and Sustainability Standards:* Increasing

regulatory pressures and sustainability standards require apple growers to adopt environmentally responsible nutrient management practices and minimize adverse environmental impacts. Compliance with nutrient management regulations, nutrient use efficiency targets, and sustainability certification requirements necessitates proactive nutrient stewardship, soil conservation measures, and nutrient recycling initiatives. Collaborative efforts between growers, researchers, policymakers, and industry stakeholders are essential for developing science-based nutrient management guidelines and promoting sustainable orchard practices [73].

5. *Future Research Directions:* To address the aforementioned challenges and advance mineral nutrition management in apple orchards, future research should focus on several key areas. These include the development of innovative nutrient delivery systems, such as controlledrelease fertilizers or fertigation technologies, tailored to apple tree nutrient requirements and environmental conditions. Additionally, exploring the role of soil microbiomes, biofertilizers, and biostimulants in enhancing nutrient cycling, soil health, and tree resilience warrants further investigation. Embracing interdisciplinary research approaches, stakeholder engagement, and knowledge exchange platforms can foster collaborative solutions and drive sustainable innovation in apple orchard management [74].

By addressing these challenges and embracing future research directions, apple growers can overcome barriers to effective mineral nutrition management, enhance orchard sustainability, and ensure the long-term viability and resilience of apple production systems.

CONCLUSION

In conclusion, this review has provided an in-depth exploration of the various aspects of mineral nutrition management in apple orchards. We have discussed the significance of mineral nutrients in sustaining tree health, enhancing fruit quality, and optimizing yield potential. By examining the role of essential nutrients such as nitrogen, phosphorus, potassium, calcium, and boron, we have highlighted their impact on tree physiology, fruit development, and post-harvest attributes.

Furthermore, we have discussed the importance of adopting integrated nutrient management strategies that encompass soil health enhancement, precision fertilization techniques, irrigation management, and soil amendment practices. Through case studies and examples, we have illustrated successful approaches to optimizing mineral nutrition inapple orchards, emphasizing the value of tailored nutrient management plans and diagnostic tools for addressing specific nutrient deficiencies or imbalances.

Despite the progress made in mineral nutrition management, several challenges and opportunities for improvement remain. Issues such as nutrient imbalances, soil degradation, climate change impacts, and technology integration present ongoing challenges that require innovative solutions and collaborative efforts. Future research directions should focus on developing sustainable orchard management practices, enhancing technology adoption, and advancing our understanding of soil-plant interactions and nutrient dynamics.

In conclusion, effective mineral nutrition management is paramount for ensuring the productivity, sustainability, and resilience of apple orchards. By embracing science-based approaches, leveraging technological innovations, and fostering interdisciplinary collaboration, we can address existing challenges and pave the way for a more sustainable and productive future in apple production.

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ТҮЙІН

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АЛМА АҒАШЫНЫҢ ӨНІМДІЛІГІН ЖӘНЕ ЖЕМІСТЕРДІҢ САҚТАЛУ МЕРЗІМІН АРТТЫРУ ҮШІН МИНЕРАЛДЫ ҚОРЕКТЕНДІРУДІ ОҢТАЙЛАНДЫРУДЫҢ ЗАМАНАУЙ ӘДІСТЕРІНЕ ШОЛУ

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Қазіргі алма бақтарында тұрақты жеміс өндіруге қол жеткізу және сапалы сақтауды қамтамасыз ету маңызды. Бұл шолуда минералды қоректендіруді оңтайландыруға арналған, өнімділікті және жемістердің сақталу мерзімін арттыруға бағытталған заманауи әдістерді зерттейді. Минералды тыңайтқыштардың тиімділігін арттыруға, теңгерімді қоректендіруді сақтауға және азот, фосфор, калий, кальций және бор сияқты негізгі қоректік заттардың маңызды рөлін түсінуге назар аудара отырып, алма бағын басқаруды жақсартудың әртүрлі стратегиялары қарастырылады. Шолу тұрақты, жоғары сапалы жеміс өніміне қол жеткізу үшін әртүрлі өсу кезеңдерінде және фенологиялық фазаларында өсімдіктердің қоректік заттарға қажеттілігін түсінудің маңыздылығын атап көрсетеді. Сонымен қатар, ол оңтайлы өнімділік пен экономикалық өміршеңдікті қамтамасыз ететін алма бақтарының нақты қажеттіліктеріне сәйкес минералды қоректену тәжірибесін бейімдеу үшін үздіксіз диагностикалық бағалаулар қажеттігін атап көрсетеді.

Түйінді сөздер: алма бақтары, минералды қоректену, өнімділікті арттыру, жемістерді сақтау, тұрақты ауыл шаруашылығы, қоректік заттарды басқару, бақ шаруашылығы.

РЕЗЮМЕ

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ОБЗОР СОВРЕМЕННЫХ МЕТОДОВ ОПТИМИЗАЦИИ МИНЕРАЛЬНОГО ПИТАНИЯ ЯБЛОКОВ ДЛЯ ПОВЫШЕНИЯ УРОЖАЙНОСТИ И ЛЁЖКОСПОСОБНОСТИ ПЛОДОВ

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Достижение устойчивого производства фруктов и обеспечение их сохранения качества имеют первостепенное значение в современных яблоневых садах. В этом обзоре рассматриваются современные методы оптимизации минерального питания с целью повышения урожайности и сохранности плодов. Рассмотрены различные стратегии улучшения управления яблоневым садом с упором на максимальную эффективность минеральных удобрений, поддержание сбалансированного питания и понимание решающей роли ключевых питательных веществ, таких как азот, фосфор, калий, кальций и бор. В обзоре подчеркивается важность понимания потребностей растений в питательных веществах на разных стадиях роста и фенологических фазах для достижения устойчивого и высококачественного производства фруктов. Кроме того, в нем подчеркивается необходимость постоянных диагностических оценок для адаптации практики минерального питания к конкретным потребностям яблоневых садов, обеспечивая оптимальную производительность и экономическую жизнеспособность.

Ключевые слова: яблоневые сады, минеральное питание, повышение урожайности, сохранение фруктов, устойчивое сельское хозяйство, управление питательными веществами, управление садом.

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