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A Comprehensive Review of Nutrient Deficiencies in Different Growth Stages of Paddy Crop

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Abstract: A systematic literature review emphasizes the significance of nutrient management in paddy crop production. It covers the crucial nutrients and their deficiencies that can substantially reduce crop growth, yield, and quality. Nutrient deficiency management challenges and limitations vary across different growth stages and are influenced by factors such as soil nutrient availability, plant genotype, and environmental conditions. Effective nutrient management strategies, such as fertilization, foliar spraying, and breeding for nutrient-use efficiency, can help mitigate these challenges and improve crop growth and yield. By applying fertilizers at the appropriate time and amount, proper nutrient management practices can enhance rice growth and yield. The review offers insights into the challenges and opportunities for improving nutrient management in paddy crop production and identifies emerging technologies to overcome these challenges. The study also contributes to the development of advanced computing technologies to predict nutrient deficiencies in various stages of paddy growth.

Keywords: Paddy Crop Production, Paddy Growth Stages, Nutrient Deficiency, Nutrient Management, Emerging Technologies

1. INTRODUCTION

A systematic literature review (SLR) was conducted to offer a comprehensive overview of critical factors associated with the growth stages of paddy crops, essential nutrients required for their growth, and nutrient deficiencies during different growth stages [1]. The review discusses the impacts of both macronutrient and micronutrient deficiencies on paddy crop production, explores management strategies, and addresses the challenges and limitations tied to nutrient deficiency management.

The review commences by examining various growth phases of paddy crops, encompassing the Nursery, vegetative, reproductive, and ripening stages[2]. Subsequently, an exploration of the significance of essential nutrients takes place, encompassing macronutrients like nitrogen, phosphorus, and potassium, as well as micronutrients such as iron, manganese, copper, zinc, boron, and silicon [1]. The roles of each nutrient in paddy crop growth and development, along with symptoms of nutrient deficiencies, are highlighted [3]. Various management strategies to counter nutrient deficiencies, such as fertilization, foliar spraying, and breeding for nutrient-use efficiency, are discussed. Moreover, the challenges and limitations of nutrient deficiency management in paddy crop production, including factors like soil nutrient availability, plant genotype, and environmental conditions, are thoroughly reviewed.In conclusion, the review synthesizes findings and discusses future research directions and emerging technologies for enhancing nutrient management in paddy crop production. It explores the potential of advanced computing technologies to predict nutrient deficiencies at various stages of paddy growth, as well as other emerging approaches to address nutrient management challenges.

For this analysis, "Rice: Nutrient Disorders and Nutrient Management," authored by A. Dobermann and T.H. Fairhurst, served as a key reference[4].The handbook sheds light on common nutrient deficiencies during paddy growth stages, detailing symptoms and best management practices for each phase. This makes it a valuable resource for effective nutrient management in rice cultivation.

2. METHODOLOGY

An SLR was conducted to gather relevant articles on the topic of nutrient management in paddy crops.

A. Planning the review

This SLR explores nutrient deficiencies during various growth stages of the paddy crop and emphasizes their effects on crop growth, yield, and quality. The research objectives include identifying essential nutrients, examining the impacts of macronutrient deficiencies, reviewing management

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strategies, assessing challenges and limitations, and identifying emerging technologies. The research questions focus on nutrient requirements, effective management strategies, challenges and limitations, advanced computing technologies, breeding for nutrient-use efficiency, and the impact of factors like soil nutrient availability, plant genotype, and environmental conditions on nutrient management.

1) Review Objectives

The following review objectives are outlined to aid readers in assessing the importance of this SLR.

- Identify the essential nutrients required for paddy crop growth at different growth stages.
- Examine the impacts of macronutrient deficiencies on paddy crop production, including stunted growth, reduced yield, and poor grain quality.
- Review management strategies for addressing nutrient deficiencies in paddy crop production, such as fertilization, foliar spraying, and breeding for nutrient-use efficiency.
- Assess challenges and limitations of nutrient deficiency management in paddy crop production across different growth stages, including soil nutrient availability, plant genotype, and environmental conditions.
- Provide insights into the significance of maintaining an appropriate balance of macronutrients and micronutrients for proper paddy crop growth and yield.
- Identify emerging technologies to improve nutrient management in paddy crop production, including the development of advanced computing technologies to predict nutrient deficiencies in various stages of paddy growth.

2) Research Questions

The first and most important step in doing a systematic review is formulating a specific research question, or SLR. Research questions should be formulated with the PIOC (population, intervention, outcomes, and context) framework in mind. Table I presents the Guidelines for Research Question Formulation. According to the table, the primary research question for the SLR would focus on determining the comprehensive study coverage of nutrient deficiency during each growth stage of paddy and identifying the suitable management strategies for addressing nutrient deficiency in paddy crop production. To further explore this main inquiry, several specific questions were formulated as follows.

- What are the nutrient requirements of paddy crops at different growth stages, and how do macronutrient and micronutrient deficiencies affect crop growth, yield, and quality?
- What are the most effective nutrient management strategies for mitigating nutrient deficiencies in paddy crop production, and how do they vary across different growth stages?
- What are the challenges and limitations of nutrient deficiency management in paddy crop production, and how can emerging technologies help overcome these challenges?
- How can advanced computing technologies be used to predict nutrient deficiencies in various stages of paddy growth, and what are the potential implications for nutrient management in paddy crop production?
- How can breeding for nutrient-use efficiency enhance the management of nutrients in paddy crop production, and what are its potential benefits and limitations?
- How do factors such as soil nutrient availability, plant genotype, and environmental conditions affect nutrient management in paddy crop production, and how can they be taken into account in nutrient management strategies?

TABLE I. Guidelines for Research Question Formulation

Guidelines	Description
Population	Paddy crops
Intervention	Nutrient requirements and management strategies
Outcome	Crop growth, yield, and quality; mitigation of nutrient deficiencies
Context	Paddy crop production, challenges and limitations, emerging technologies, advanced computing technologies, breeding for nutrient-use efficiency and factors affecting nutrient management

B. Conducting the Review

1) The Selection Process for Review Articles

The study aimed to identify the findings on nutrient deficiencies in various stages of paddy crop by conducting a comprehensive review of related articles. Initially, 107 paddy-related articles were downloaded from various research databases. Seven filters were used to narrow down the selection to 75 articles, which underwent a quality assessment. The filters included the target keyword, publication year, and type of publication, looking for duplicates examining article titles, abstracts, keywords, and checking the references of the articles that were selected and performing a final assessment of the article's caliber. The publications that were published between 2000 and 2023 were taken into consideration for this study due to the field's rapid growth. The selected 75 articles were thoroughly reviewed to identify their findings on nutrient deficiencies in various

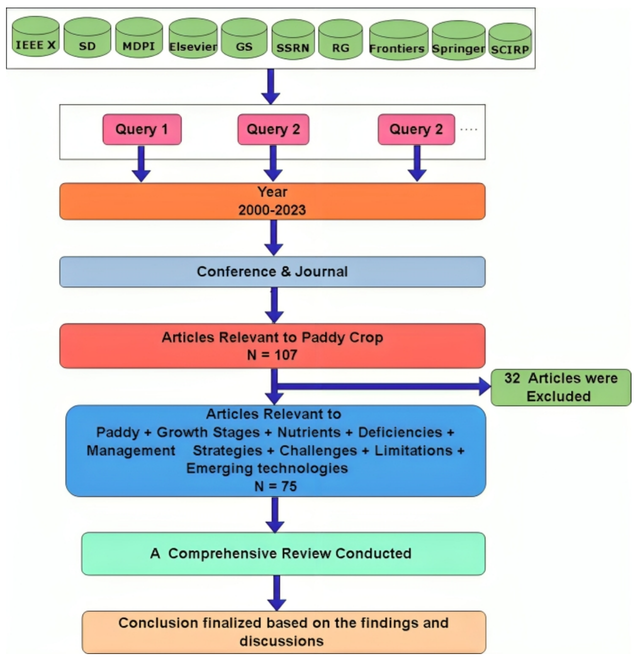

Figure 1. The Process of Article Selection

stages of paddy crop. Figure 1 shows the process of article selection.

3. LITERATURE REVIEW

A. *Critical Factors Associated with the Growth Stages of the Paddy*

Paddy has a growth period of 3 to 6 months. During this period, rice progresses through four separate growth phases: nursery, vegetative, reproductive, and ripening[5]. The seedling and germination stages comprise the nursery phase. The vegetative phase consists of the seedling, tillering, and stems elongation stages. The reproductive phase consists of the panicle initiation, booting, and flowering stages. The ripening phase consists of the milk, dough, and matures stages. In a tropical environment, a 120-day variety spends approximately 60 days in the vegetative phase, 30 days in the reproductive phase, and 30 days in the maturation phase. Figure 2 depicts the various phases and stages of paddy growth.

1) *Nursery Phase*

The nursery phase of paddy growth, including the seed and germination stages, serves an important role in the overall success of the cultivation process.

Seed Stage:

The seed stage is the first stage of the nursery phase, and it involves selecting high-quality seeds for planting. Therefore, selecting good quality seeds is critical in ensuring a successful paddy crop[6]. Good quality seeds have high germination rates and produce healthy seedlings, which result in high yields during the main growth stages[6].During the

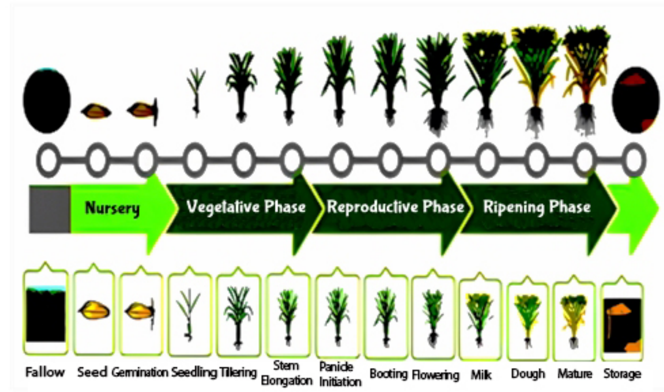

Figure 2. Various Phases and Stages of Paddy Growth

seed stage, the selected seeds are treated with fungicides and insecticides to protect them from pests and diseases[7]. This treatment ensures that the seedlings are not attacked by pests and diseases, which can lead to stunted growth and poor yields.

Germination Stage:

The germination stage is a crucial stage in the growth of paddy, during which the seedling emerges from the seed and grows into a young plant. Proper management of water, nutrients, temperature, and root exudates during this stage is essential for the proper development of the seedling and for high yield. [8] emphasizes the importance of nutrient management during the germination stage for proper development of the seedling and high yield.

2) *Vegetative Phase*

The vegetative phase of paddy growth is a crucial stage in the crop's development and growth.It includes the seedling, tillering, and stem-lengthening stages.

Seedling Stage:

The seedling stage marks the beginning of the vegetative phase of paddy growth. During this stage, the young seedlings develop a strong root system and grow leaves[5]. Proper care and attention during this stage are crucial in ensuring healthy and robust seedlings that will translate into high yields during the main growth and development stages[8]. During the seedling stage, it is important to provide the seedlings with adequate nutrition through the application of fertilizers [3]. Proper irrigation and drainage are also crucial to ensure that the soil remains moist, providing the ideal growing environment for the seedlings[9].

Tillering and Stem Elongation Stage:

During the Tillering and Stem Elongation stages in paddy crops, additional stems and grains are produced, leading to higher yields. To ensure healthy plants that can maximize sunlight for photosynthesis, it is important to provide adequate nutrition and water. Managing pests and diseases is also crucial to prevent plant damage. The Tillering stage involves the formation of lateral shoots called tillers, which grow from the plant's base. This stage is characterized by rapid growth of the main stem and tillers, resulting in increased plant height [5, 9].

3) Reproductive Phase

The reproductive phase of paddy growth is the most critical stage, as it determines the yield potential of the crop. This phase can be divided into three stages: panicle initiation, booting, and flowering.

Panicle Initiation Stage:

The Panicle Initiation Stage is a crucial stage in the development of paddy crops, signaling the start of the reproductive phase[7]. At this stage, spikelet primordia start forming within the panicle, and the plant begins to produce its inflorescence. Adequate nutrients and water are crucial during this stage to ensure that the panicles develop fully, leading to higher yields during the harvest. The Panicle Initiation Stage typically occurs around 60 to 70 days after transplanting or 95 to 105 days after sowing[7].

Booting Stage:

The panicle booting stage in paddy crop is a crucial stage where the panicle emerges from the flag leaf sheath and the primary panicle branches start to elongate. According to [7], nutrient deficiencies during this stage can lead to reduced grain quality and yield. Proper care and attention during this stage are crucial in ensuring that the panicles grow fully, resulting in higher yields during the harvest. Several articles discuss this stage in paddy crop and its related factors, including [4, 8, 10, 11, 12, 13].

Flowering Stage:

Flowering is a crucial stage in the maize crop's growth cycle because this is when the plant starts producing flowers and eventually grain. During this stage, adequate care is crucial to ensure successful pollination, which results in higher yields during the harvest. Therefore, it is important to understand the factors that affect the flowering stage and to take the necessary steps to optimize the yield. Numerous studies on the flowering stage of the paddy crop have been conducted, including those by [14, 15, 16].

4) Ripening Phase

The ripening phase of paddy growth is the final stage in the course of a plant's life. This phase is marked by the development and maturation of the grain. The ripening phase has three sub-stages: the milk stage, the dough stage, and the mature stage.

Milk Stage:

The milk stage is a crucial stage in the development of paddy crops because the grains are still maturing and require optimal growing conditions to attain their optimum size and weight. During this stage, the grains are filled with a milky fluid. Several articles including [7, 8, 12, 17], and [14] discuss the importance of the milk stage in determining the final yield of the crop, as well as its critical role in nutrient uptake and utilization.

Dough Stage:

The dough stage in paddy crop refers to a developmental stage where the grain is in a soft, dough-like consistency and is still developing. At this stage, the grain has a moisture content of around 35-40% and is still filling with starch. This stage occurs after the milk stage and before the hard dough stage [5].

Mature Stage:

The mature stage is when the grains reach their final size and weight, and the plant begins to dry out. At this point, the grain is considered fully developed, and it is ready for harvest. In order to prevent the grain from being harmed or lost as a result of environmental factors such as rain or wind, careful administration is required during the mature stage [5].

B. Essential Nutrients of Paddy Crop

Paddy requires primary plant nutrients such as nitrogen, phosphorus, and potassium; secondary plant nutrients such as calcium, magnesium, and sulphur; and trace elements such as iron, manganese, copper, zinc, and boron [8]. Major or macronutrients are the primary and secondary nutrient elements. This classification is determined by their relative abundance, not their relative significance. Macronutrients are required by plants in large quantities, typically exceeding 0.1% of the plant's dried weight. The micronutrients are required in modest amounts, but they are essential as the primary plant nutrients.There are numerous nutrients required for the development and proliferation of paddy plants. Figure 3 shows the classification of essential nutrients for paddy crop.

1) Macro-Nutrients

a. Primary Nutrients

Nitrogen:

Nitrogen is crucial for paddy crops [18]. It supports vital processes like photosynthesis and protein synthesis [14, 19]. Sufficient nitrogen improves growth, tillering, and yield[20]. Inadequate nitrogen leads to stunted growth and lower yield [21]. Nitrogen uptake is highest during the vegetative and reproductive stages [5, 22]. Proper management optimizes productivity and minimizes pollution [9]. Organic and inorganic fertilizers are nitrogen sources [23]. Timing and method of application affect nutrient availability. Split application improves efficiency and reduces losses [9]. Integrating nitrogen management with balanced fertilization and optimized irrigation enhances efficiency and reduces

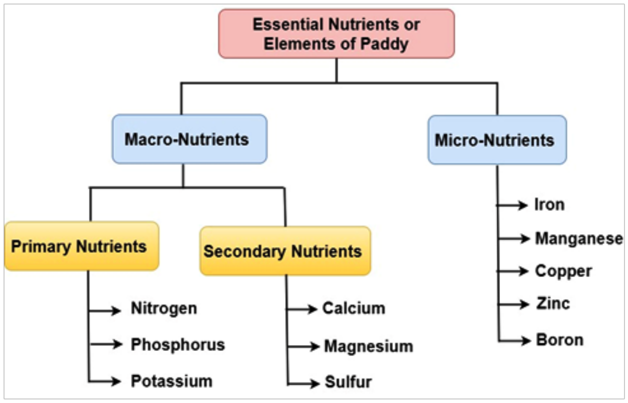

Figure 3. Classification of Essential Nutrients for Paddy Crop

impacts [24]. Sustainable paddy production requires understanding nitrogen's role and adopting appropriate practices [25, 26].

Phosphorus:

Phosphorus is an essential nutrient for paddy crop growth and development [10, 20]. It plays a crucial role in various physiological processes, including energy transfer, photosynthesis, and root development [7, 14, 15]. Phosphorus deficiency can result in stunted growth and reduced yields in paddy crops [21, 27]. Adequate phosphorus availability is necessary for optimal rice production, and proper nutrient management practices, such as foliar spray and rhizosphere processes, can enhance phosphorus uptake and utilization [28, 3, 14]. Furthermore, the enrichment of periphyton with phosphate-solubilizing microorganisms can improve phosphorus concentration and micronutrient uptake in paddy soils [29, 30]. Understanding and addressing the phosphorus requirements of paddy crops are essential for achieving sustainable and high-yielding rice production[5, 9].

Potassium:

Potassium is an essential nutrient for paddy crops, playing a vital role in their growth and development. It activates enzymes, regulates osmotic potential, and maintains cell turgor pressure [15, 31]. Potassium also enhances photosynthesis, water-use efficiency, and the plant's ability to withstand abiotic stresses like drought and salinity [3, 16]. Its significance varies during different growth stages, promoting root growth, leaf area, and nitrogen uptake in the vegetative stage [32, 19], and ensuring proper pollen development, pollination, and grain formation during the reproductive stage [15].Organic manures and biochar can enhance potassium retention and release in the soil, improving its availability to plants [33, 32, 34]. Proper water management plays a vital role in preventing potassium leaching through excessive flooding and avoiding water stress that can affect potassium uptake [23].

b. Secondary Nutrients

Calcium:

Calcium plays a crucial role in paddy crop growth, including cell elongation and division, root and shoot growth, pollen germination, and fruit setting, according to [2, 7, 8, 17]. Calcium deficiency causes stunted growth, lower yield, inferior grain quality, and susceptibility to parasites and diseases.These references provide detailed information on the role of calcium in paddy crop growth, calcium deficiency symptoms, and how to manage calcium deficiency in paddy crops.

Magnesium:

Magnesium is essential for paddy crop growth, and it is in dispensable in the photosynthesis process and involves multiple enzymatic reactions, leading to increased yields, according to [15]. [3, 7] also highlight the importance of magnesium in rice plant growth and suggest foliar fertilization as a viable option for improving magnesium uptake in rice crops.

Sulfur:

According to [21], sulfur is necessary for chlorophyll synthesis, amino acid and protein production, and root growth, and its deficiency can lead to reduced plant growth, yield, and quality.

2) Micro-Nutrients

Iron:

Iron is essential for the development and growth of plants, including the production of chlorophyll and photosynthesis in paddy plants. Its deficiency can cause stunted growth in paddy plants, and toxicity can occur in wetland rice. [10]found that some rice cultivars can mobilize iron from the soil through root exudates containing organic acids. [21] emphasized iron as an essential micronutrient for optimal paddy growth.

Manganese:

Manganese is involved in the process of photosynthesis and helps in the breakdown of carbohydrates.The growth of paddy requires manganese, as highlighted in various studies. [21] Reported that manganese deficiency can result in stunted growth in plants, including paddy. [11] Described manganese as one of the micronutrients essential for crop growth in India. Manganese was one of the crucial elements for rice growth, according to research [2] into the growth and yield formation of rice.

Copper:

Copper is an essential micronutrient for plant growth.In rice production systems, copper deficiency negatively affects crop productivity [2]. Micronutrient deficiencies, including copper, can lead to stunting syndrome in plants. Stunting syndrome is characterized by reduced cell elongation and impaired tissue differentiation.Adequate copper supplementation in agriculture is crucial for promoting healthy plant growth in rice production [21].

Zinc:

According to [27], a review paper on zinc's role in rice production systems, zinc fertilizers can increase crop output by as much as 33%. Zinc is crucial for plant development because it helps make chlorophyll, aids in leaf and stem growth, and is involved in the creation of plant hormones.Zinc availability is also influenced by soil organic matter content, as organic matter can complex with zinc and impede its uptake by plants [27, 19].Other nutrients, such as phosphorus, nitrogen, and organic matter, can also influence zinc availability in paddy soils [29, 35, 33].Proper nutrient management, including balanced fertilization and organic amendments, can improve zinc availability and uptake by paddy crops [29, 22, 36].

Boron:

According to [21], micronutrient deficiencies, such as boron, can lead to stunted growth in plants. Boron is necessary for the formation of cell walls and is involved in the formation of reproductive structures. Moreover, boron enhances the efficiency of nitrogen and phosphorus use by plants [11, 37].Integrated nutrient management strategies can also contribute to improving boron utilization and overall nutrient balance in paddy fields [24, 38].

C. Overview of Nutrient Requirements at Different Growth Sages of Paddy Crop

Paddy crop has different requirements for different nutrients during various growth stages. Here is a brief overview of nutrient requirements at different growth stages of paddy crop

Nitrogen:

Nitrogen is essential for vegetative growth and yield formation in rice. It is needed in large amounts during tillering and panicle initiation stages [20, 39].

Phosphorus:

Variable amounts of phosphorus are required by rice crops at various growth phases. It is lowest in the early stages of plant development and peaks during the vegetative phase. Reproduction requires slightly fewer nutrients than vegetative growth [2, 7, 8, 40].

Potassium:

Potassium is essential for plant growth, efficient water use, and yield formation. The rice plant absorbs more potassium during the grain-filling stage [31].Applying potassium fertilizers at the appropriate growth stages to meet the crop's specific nutrient demands [8].

Calcium:

Calcium is essential for plant cell division, elongation, and the development of roots. It is indispensable for the effective function of cell membranes and the transport of nutrients within the plant [8, 41].

Magnesium:

Magnesium is required for the synthesis of chlorophyll and the maintenance of cell membranes. During the reproductive phase of rice [15], it is required in considerable amounts. Magnesium deficiency in Seedling Stage can result in stunted growth and reduced nutrient uptake capacity [21]. Magnesium deficiency during Grain Filling Stage can lead to reduced grain weight and lower grain quality[27].

Sulfur:

Sulphur is indispensable for protein synthesis. vitamins, and enzymes in rice. It is required in large amounts during the early vegetative phase of rice[7]. Sulfur deficiency during Reproductive Stage can result in reduced panicle size, lower grain weight, and decreased grain yield [7]. It is required during Maturation Stage for the synthesis of storage proteins and carbohydrates, which contribute to grain filling and quality [10].

Iron:

Iron is important for chlorophyll synthesis and for the proper functioning of metabolic processes. Iron toxicity can occur in wetland rice, and the deficiency of iron can lead to chlorosis and stunted growth [12, 13].During the early growth stage, iron plays a crucial role in seed germination, chlorophyll synthesis, and root development [9]. Iron deficiency during vegetative stage can result in chlorosis, reduced leaf area, and decreased photosynthetic activity [29].

Manganese:

Manganese is necessary for the formation of chloroplasts and for the metabolism of nitrogen. Manganese deficiency can lead to Interveinalchlorosis and poor plant growth[7].Manganese is essential for the synthesis of chlorophyll and other photosynthetic pigments, which are vital for energy production and carbohydrate metabolism [25].

Copper:

Copper is essential for the proper functioning of enzymes involved in respiration, photosynthesis, and lignin synthesis. Copper deficiency can lead to stunted growth and reduced yields[7].As the paddy crop enters the vegetative growth stage, the demand for copper increases [42]. Copper is essential for chlorophyll synthesis, which is crucial for photosynthesis and carbohydrate production [43]. It also acts as a cofactor for various enzymes involved in plant growth and development processes [44].

Zinc:

Zinc is essential for plant growth and development, including chlorophyll synthesis, enzyme activity, and protein synthesis. Zinc deficiency can lead to stunted growth and reduced yields[6, 27, 37].Adequate zinc supply is crucial for promoting root growth and nutrient uptake efficiency in young plants [45].

Boron:

Boron is required for cell wall synthesis and cell division. Boron deficiency can lead to reduced root growth and yield[3]. During the seedling stage, the paddy crop has a high demand for boron to support root development and early growth [46]. Insufficient boron at this stage can lead to poor root establishment, stunting, and reduced plant vigor [47].In the vegetative stage, the paddy crop requires an adequate supply of boron for leaf expansion, tillering, and biomass accumulation [48]. Table II Clearly shows the requirements of Major and its supportive Nutrients in various growth stages of Paddy.

TABLE II. Requirements of Major and its Supportive Nutrients in Various Growth Stages of Paddy

Stages of Growth	**Requirements of Major Nutrient**	**Supporting Nutrients Required**
Seed Germination	N, P and K Carbohydrates, Proteins, N and P	Ca and Zn Mg
Seedling	N, P and K	S and B
Tillering	N, P and K	Fe and Mg
Stem Elongation	N, P and K	Cu and Cl
Panicle Initiation	N, P and K	Si and Na
Booting	N, P and K	Co and Ni

(N: Nitrogen, P: Phosphorus, K: Potassium, Ca: Calcium, Zn: Zinc, Mg: Magnesium, S: Sulfur, B: Boron, Fe: Iron, Cu: Copper, Cl: Chlorine, Si: Silicon, Na: Sodium, Co: Cobalt, Ni: Nickel, Mn: Manganese)

D. Impacts and Management of Macronutrient Deficiencies in Paddy Crop Production

Paddy crops require essential macronutrients such as nitrogen, phosphorus, potassium, sulphur, calcium and magnesium for optimal growth and yield. Macronutrient deficiencies can lead to stunted growth, low yield, and poor grain quality. Here are some examples of the impacts and management strategies for macronutrient deficiencies in paddy crop production. The critical level and optimal range values for nutrients in paddy crop help predict nutrient deficiencies in different growth stages. Soil testing is the primary method to determine the critical level of nutrients, while plant tissue analysis helps detect nutrient content at various growth stages. Leaf color charts provide visual indication of nitrogen status, and farmers can develop fertilizer and nutrient management plans based on critical levels and optimal ranges to ensure optimal nutrient supply for crop growth and yield.

Nitrogen Deficiency:

Nitrogen is a vital macronutrient for rice production, and its deficiency can cause stunted growth, yellowing of leaves, and poor tillering. Appropriate nitrogen management practices, such as applying nitrogen fertilizer at the optimal time and quantity, can increase yield and grain quality [20, 49]. Nitrogen is an essential macronutrient that plays a crucial role in various physiological processes, including photosynthesis, protein synthesis, and enzyme activity [50, 32]. Insufficient nitrogen availability can lead to stunted plant growth, reduced tiller production, and decreased grain yield [51, 52].Table III shows the Critical levels and optimum ranges for Nitrogen deficiency in rice plant tissue.

TABLE III. Critical Levels and Optimum Ranges for Nitrogen Deficiency in Rice Plant Tissue

Stages of Growth	**Part of Plant**	**Critical level (%)**	**Optimum (%)**
Tillering-Panicle initiation	Y leaf	Below 2.5	2.9 to 4.2
Flowering	Flag leaf	Below 2.0	2.2 to 3.0
Mature	Straw	-	0.6 to 0.8

Phosphorus Deficiency:

Phosphorus deficiency in plants hampers development, resulting in insufficient root growth, delayed maturity, and reduced tillering. Adding phosphorus-based fertilizers enhances rice growth and production[4].Phosphorus is essential for vital plant processes such as energy transfer, photosynthesis, and nutrient absorption [44, 53].Insufficient phosphorus in paddy crops leads to stunted growth, delayed maturity, and reduced tillering [46, 54, 55].Table IV shows

TABLE IV. Critical Levels and Optimum Ranges for Phosphorus Deficiency in Rice Plant Tissue

Stages of Growth	**Part of Plant**	**Critical Level (%)**	**Optimum (%)**
Tillering-Panicle initiation	Y leaf	Below 0.10	0.20 to 0.40
Flowering	Flag leaf	Below 0.18	0.20 to 0.30
Mature	Straw	Below 0.06	0.10 to 0.15

the Critical levels and optimum ranges for Phosphorus deficiency in rice plant tissue.

Potassium Deficiency:

Potassium is important for plant growth and stress tolerance, and its deficiency can lead to reduced yield, lodging, and susceptibility to diseases. Proper potassium management practices, such as applying potassium fertilizer at the optimal time and quantity, can increase yield and grain quality [31].Potassium deficiency can disrupt water balance, nutrient transport, and carbohydrate metabolism in plants [42, 48].Regular soil testing and nutrient analysis can provide insights into the potassium status of the soil [56].Table V shows the Critical levels and optimum ranges for Potassium deficiency in rice plant tissue.

TABLE V. Critical Levels and Optimum Ranges for Potassium Deficiency in Rice Plant Tissue

Stages of Growth	Part of Plant	Critical Level (%)	Optimum (%)
Tillering-Panicle initiation	Y leaf	Below 1.5	1.8 to 2.6
Flowering	Flag leaf	Below 1.2	1.4 to 2.0
Mature	Straw	Below 1.2	1.5 to 2.0

Calcium Deficiency:

Calcium is important for cell wall development and structural integrity, and its deficiency can lead to reduced growth, quality, and yield. Calcium fertilizers and soil amendments can increase calcium availability and rice growth [8].

TABLE VI. Critical Levels and Optimum Ranges for Calcium Deficiency in Rice Plant Tissue

Stages of Growth	Part of Plant	Critical Level (%)	Optimum (%)
Tillering-Panicle initiation	Y leaf	Below 0.15	0.2 to 0.6
Maturity	Straw	Below 0.15	0.3 to 0.5

Calcium deficiency weakens the plant's defense mechanisms, making it more susceptible to diseases and pest attacks [48].Maintaining optimal nutrient balance, especially proper ratios of calcium to other nutrients, is crucial to prevent calcium deficiency in paddy crops [57].Table VI shows the Critical levels and optimum ranges for Calcium deficiency in rice plant tissue.

Magnesium Deficiency:

Magnesium is important for chlorophyll synthesis and photosynthesis, and its deficiency can lead to yellowing of leaves and reduced growth. Magnesium fertilizer can boost rice growth and harvest [15].Incorporating organic matter into the soil can enhance magnesium availability and improve nutrient uptake efficiency [34].Table VII shows the Critical levels and optimum ranges for Magnesium deficiency in rice plant tissue.

TABLE VII. Critical Levels and Optimum Ranges for Magnesium Deficiency in Rice Plant Tissue

Stages of Growth	Part of Plant	Critical Level (%)	Optimum (%)
Tillering-Panicle initiation	Y leaf	Below 0.12	0.15 to 0.30
Tillering-Panicle initiation	Shoot	Below 0.13	0.15 to 0.30
Mature	Straw	Below 0.10	0.20 to 0.30

Sulfur Deficiency:

Sulfur is essential for protein synthesis and tolerance to stress, and its deficiency can result in decreased growth and yield. Sulfur fertilizer application can enhance rice growth and yield [8].Sulfur deficiency in paddy soils is often associated with high pH levels and poor organic matter content. Sandy soils and intensively cultivated paddy fields are particularly susceptible to sulfur deficiency [58].Table VIII shows the critical levels and optimum ranges for Sulfur deficiency in rice plant tissue.

TABLE VIII. Critical Levels and Optimum Ranges for Sulfur Deficiency in Rice Plant Tissue

Stages of Growth	Part of Plant	Critical Level (%)	Optimum (%)
Tillering	Y leaf	Below 0.16	-
Tillering	Shoot	Below 0.11	0.15 to 0.30
Flowering	Flag leaf	Below 0.10	0.10 to 0.15
Flowering	Shoot	Below 0.07	-
Mature	Straw	Below 0.06	-

E. Impacts and Management of Micronutrient Deficiencies in Paddy Crop Production

Micronutrient deficiencies in paddy crop production can significantly affect growth, yield, and quality. The following are the impacts and management strategies of some micronutrient deficiencies in paddy crop production.

Iron Deficiency:

It can cause yellowing of leaves, stunted growth, and reduced yield.The application of iron fertilizers, including foliar sprays and chelated iron, can effectively manage iron deficiency [12, 13].Iron deficiency in paddy crops leads to various detrimental effects on plant growth and development [59]. Chlorosis, characterized by yellowing of leaves with green veins, is the primary symptom of iron deficiency [59, 60].Table IX Shows the Critical levels and optimum ranges for Iron deficiency in rice plant tissue.

TABLE IX. Critical Levels and Optimum Ranges for Iron Deficiency in Rice Plant Tissue

Stages of Growth	Part of Plant	Critical Level (mg/kg)	Optimum (mg/kg)
Tillering-Panicle initiation	Y leaf	Below 70	75 to 150
Tillering-Panicle initiation	Shoot	Below 50	60 to 100

Zinc Deficiency:

It can lead to poor growth, delayed maturity, and reduced grain yield. Zinc sulphate and zinc oxide fertilizers applied to the soil improve zinc absorption and translocation in rice plants [6, 27].Zinc-deficient plants often have reduced tiller numbers, decreased panicle length, and lower grain yields [27, 47]. Table X shows the Critical levels and optimum ranges for Zinc deficiency in rice plant tissue.

TABLE X. Critical Levels and Optimum Ranges for Zinc Deficiency in Rice Plant Tissue

Stages of Growth	Part of Plant	Critical Level (mg/kg)	Optimum (mg/kg)
Tillering	Y leaf	Below 20	25 to 50
Tillering	Whole shoot	Below 10	25 to 50

Boron Deficiency:

It can cause brittle leaves and stem, which can lead to yield losses. The use of boron fertilizers, including borax and boric acid, can improve crop growth and yield [4].Boron deficiency in paddy crops has several negative impacts on plant growth and development. Studies have shown that boron deficiency can result in stunted growth, reduced tillering, and poor panicle development [61].Seed treatment is an effective method to prevent boron deficiency symptoms in the early stages of crop growth [52].Table XI shows the Critical levels and optimum ranges for Boron deficiency in rice plant tissue.

TABLE XI. Critical Levels and Optimum Ranges for Boron Deficiency in Rice Plant Tissue

Stages of Growth	Part of Plant	Critical Level (mg/kg)	Optimum (mg/kg)
Tillering-Panicle initiation	Y leaf	Below 5	6 to 15
Mature	Straw	Below 3	-

Manganese Deficiency:

It can cause yellowing and necrosis of leaves, which can lead to reduced photosynthesis and yield. Soil application of Manganese fertilizers, including manganese sulfate and manganese oxide, can improve Manganese uptake and alleviate Manganese deficiency [8].Its deficiency can result in visible symptoms such as interveinalchlorosis, reduced plant height, and poor grain filling [62].Table XII shows the Critical levels and optimum ranges for Manganese deficiency in rice plant tissue.

TABLE XII. Critical Levels and Optimal Ranges for Manganese Deficiency in Rice Plant Tissue

Stages of Growth	Part of Plant	Critical Level (mg/kg)	Optimum (mg/kg)
Tillering-Panicle initiation	Y leaf	Below 40	40 to 700
Tillering	Shoot	Below 20	50 to 150

Copper Deficiency:

It can cause leaf chlorosis, wilting, and reduced growth. The use of copper fertilizers, including copper sulfate and copper oxide, can improve Copper uptake and reduce Copper deficiency symptoms [11]. Balancing the overall nutrient management in paddy crop production is crucial for mitigating copper deficiency [63].Adequate levels of other essential nutrients, such as zinc, iron, manganese, and molybdenum, are necessary for optimal copper uptake and utilization by paddy crops [64]. Table XIII shows the Critical levels and optimum ranges for Copper deficiency in rice plant tissue.

TABLE XIII. Critical Levels and Optimum Ranges for Copper Deficiency in Rice Plant Tissue

Stages of Growth	Part of Plant	Critical Level (mg/kg)	Optimum (mg/kg)
Tillering-Panicle initiation	Y leaf	Below 5	7 to 15
Mature	Straw	Below 6	-

Silicon Deficiency:

It can cause reduced growth, yield, and quality. The application of silicon fertilizers, including calcium silicate and potassium silicate, can improve plant growth and yield and enhance resistance to abiotic and biotic stresses [65]. Silicon deficiency leads to decreased grain yield, lower panicle number, and reduced percentage of filled grains [66]. Table XVI shows the Critical levels and optimum ranges for Silicon deficiency in rice plant tissue.

TABLE XIV. Critical Levels and Optimum Ranges for Silicon Deficiency in Rice Plant Tissue

Stages of Growth	Part of Plant	Critical Level (mg/kg)	Optimum (mg/kg)
Tillering-Panicle initiation	Y leaf	Below 5	-
Mature	Straw	Below 5	8 to 10

F. Challenges and Opportunities in Nutrient Deficiency Management

Management of nutrient deficiency is a crucial aspect of paddy crop production, as nutrient deficiencies can have a significant impact on plant growth and yield [57, 63, 64, 67, 68, 69, 70].Nutrient disorders and management in rice are essential to ensure optimal crop growth [4, 71]. Micronutrient deficiencies, such as iron toxicity, can lead to growth retardation and stunting syndrome in crops [6, 21]. Understanding the variations in nutrient absorption mechanisms among different rice cultivars at various growth stages is crucial [10, 72]. Additionally, the prevalence of soil and crop micronutrient deficiencies, particularly in India, emphasizes the need for effective nutrient management strategies [11, 73]. Analyzing the growth and yield of rice in specific cultivation systems can shed light on the significance of nutrient management. For example, studying rice in the water-saving ground cover rice production system highlights the importance of nutrient management for sustainable crop production [2, 74]. Evaluating the impact of foliar spraying with nutritional solutions on rice subjected to saltwater stress can provide insights into managing nutrient deficiencies under challenging conditions [28, 75]. The yield physiology of rice is heavily influenced by nutrient availability, making nutrient management essential for maximizing crop productivity [7]. Furthermore, investigating the effects of adding nitrogen to lowland rice soil can enhance our understanding of nutrient dynamics and optimization in rice cultivation [20]. Managing soil nutrients is not only crucial for crop growth but also for environmental sustainability. Rice plants play a significant role in regulating methane emission mechanisms, underscoring the importance of nutrient management in reducing greenhouse gas emissions [17]. Mitigating iron toxicity in wetland rice and understanding the role of other nutrients in alleviating its effects is essential for maintaining crop health [12]. Additionally, exploring the molecular mechanisms of zinc absorption and transport in rice and reviewing zinc nutrition in rice production systems contribute to effective nutrient management practices [15, 27]. Practical guidelines for nutrient management in rice can provide farmers with valuable insights and recommendations [8]. Understanding the rhizosphere processes associated with plant nutrition in China's main cropping systems can further enhance nutrient management strategies [13]. The relationship between magnesium and potassium in rice nutrition is significant, and magnesium deficiency can impact crop growth [6]. Evaluating the prospective health benefits of Golden Rice, a genetically modified variety rich in vitamin A, highlights the potential of nutrient-enriched crops in addressing nutritional deficiencies [16].To effectively address nutrient deficiency in rice crop production, a thorough understanding of nutritional diseases, absorption mechanisms, and effective management approaches are required.Studies on specific cultivation methods, such as saltwater stress situations and water-saving ground cover rice production, as well as information on nutrient uptake efficiency and micronutrient deficiencies, can be used to optimise crop development and output [30, 33, 34, 35, 38, 60].

G. Discussion of Findings and Synthesis of Results

This SLR highlights the nutrient requirements of paddy crops at different growth stages, the impacts of macronutrient deficiencies on crop production, and the corresponding management strategies. Nitrogen is essential for vegetative growth and yieldformation in rice, while potassium is important for water use efficiency and yield formation. Calcium is essential for cell division in plants, elongation, and root system development, while magnesium is essential for chlorophyll production and maintenance of cell membranes. Both sulphur and phosphorus are crucial for plant development and growth, but protein synthesis and stress resistance would not be possible without them. Deficiencies in these macronutrients can lead to stunted growth, reduced yield, and poor grain quality. Proper nutrient management practices, such as applying fertilizers at the right time and amount, can improve rice growth and yield. In addition to the larger macronutrients, micronutrients including iron, manganese, copper, zinc, boron, and silicon are essential for successful crop growth. Iron is required for the production of chlorophyll.while manganese is necessary for the formation of chloroplasts and the metabolism of nitrogen. Copper is essential for enzyme functioning, while zinc is necessary for chlorophyll synthesis, enzyme activity, and protein synthesis.Boron is required for cell wall synthesis and cell division, while molybdenum is necessary for the conversion of nitrates to ammonium in the plant. There is evidence that silicon enhances plant growth and yield. The synthesis highlights the significance of nutrient management in paddy crop production for achieving optimal growth and yield. The proper application of nutrients at the right time and amount can help overcome nutrient deficiencies, leading to healthy crop growth, and improved grain quality. As nutrient

TABLE XV. Critical Level of Nutrient Deficiency at Different Growth Stages of Rice Plant

Nutrients	Stages of Growth	Part of Plant	Critical Level (%)
N	Tillering, Stem Elongation, Panicle initiation	Y Leaf	2.50
	Flowering	Flag Leaf	2.0
	Mature	Straw	-
P	Tillering, Stem Elongation, Panicle initiation	Y Leaf	0.10
	Flowering	Flag Leaf	0.18
	Mature	Straw	0.06
K	Tillering, Stem Elongation, Panicle initiation	Y Leaf	1.5
	Flowering	Flag Leaf	1.2
	Mature	Straw	1.2
Ca	Tillering, Stem Elongation, Panicle initiation	Y Leaf	0.15
	Mature	Straw	0.15
Mg	Tillering, Stem Elongation, Panicle initiation	Y Leaf	0.12
	Tillering, Stem Elongation, Panicle initiation	Shoot	0.13
	Mature	Straw	0.10
S	Tillering	Y Leaf	0.16
	Tillering	Shoot	0.11

requirements differ at different growth stages, it is essential to understand the crop's nutritional needs at each stage to achieve optimal growth and yield. Additionally, micronutrients play an important part in a plant's development and growth, and their deficiencies can lead to reduced yields. Therefore, it is essential to maintain an appropriate balance of macronutrients and micronutrients for proper crop growth and yield. This SLR established that nitrogen, phosphorus, and potassium are the three major nutrients essential to the development of paddy.In addition to preserving N, P,

TABLE XVI. Critical Level of Nutrient Deficiency at Different Growth Stages of Rice Plant

Nutrients	Stages of Growth	Part of Plant	Critical Level (%)
Fe	Tillering, Stem Elongation, Panicle initiation	Y Leaf	70 mg/kg
	Tillering, Stem Elongation, Panicle initiation	Shoot	50 mg/kg
Zn	Tillering	Y Leaf	20 mg/kg
	Tillering	Whole Shoot	10 mg/kg
B	Tillering, Stem Elongation, Panicle initiation	Y Leaf	5 mg/kg
	Mature	Straw	3 mg/kg

K levels during development, the levels of other essential nutrients including Ca, Zn, Mg, S, B, Fe, Cu, Cl, Si, Na, Co, and Ni are also supported. In addition, this research details the precise nutrient concentrations needed at various points during paddy's development. Tables XV and XVI shows the overall critical level of Nutrient deficiency at different growth stages of rice plant.

TABLE XVII. Uptake Levels of Major Nutrients in Paddy Growth Phases

Nutrient	Vegetative Total	Reproductive Total	Ripening Total
N	2.33	16.82	1.91
P	0.22	1.92	0.59
K	1.69	16.52	1.57
Ca	0.51	5.50	1.54
Mg	0.38	4.14	2.51

Monitoring the uptake levels of nutrients in paddy plants is crucial for optimizing nutrient management practices and predicting nutrient deficiencies during different growth stages. Nutrient uptake varies depending on the growth stage of the crop, with nitrogen, phosphorus, and potassium being essential during the early vegetative phase, while potassium and phosphorus are required during the reproductive phase. By analyzing nutrient uptake levels, farmers can determine the optimal rates and timing of fertilization to prevent deficiencies and achieve higher yields and quality

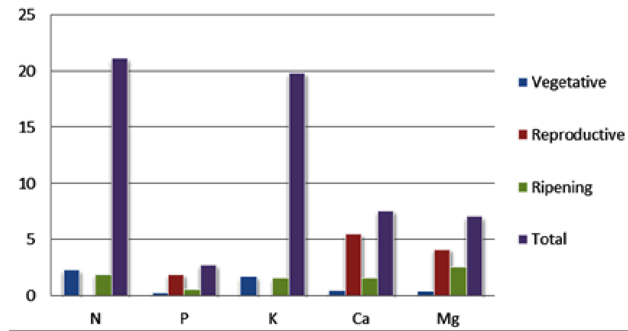

Figure 4. Uptake Levels of Major Nutrients in Paddy Growth Phases

in their crops. Table XVII and Figure 4 show the uptake levels of major nutrients, such as N, P, K, Ca, and Mg, in the phases of paddy growth.

H. Future Research Directions and Emerging Technologies

The refinement of existing nutrient management practices may be a potential focus of future study in the area of paddy crop production. This involves using advanced technologies such as remote sensing and precision agriculture to apply nutrients in a more targeted and efficient manner. This approach can help optimize nutrient use efficiency, reduce fertilizer wastage, and minimize environmental pollution. Another area of research could be the development of new fertilizer formulations that are more efficient and sustainable. For example, slow-release fertilizers and Nano fertilizers have been shown to reduce nutrient losses and increase nutrient use efficiency. Developing sustainable and eco-friendly fertilizers that are not harmful to the environment is also an important area of research.Moreover, there is a need to develop nutrient management practices that are suitable for different rice cultivars and soil types. Different rice cultivars have varying nutrient requirements, and soil properties can affect nutrient availability and uptake by crops. Therefore, developing customized nutrient management practices based on specific rice cultivars and soil types can help achieve optimal growth and yield. Finally, it is essential to comprehend the long-term effects of nutrient management practices on soil health and the surrounding ecosystem. Excessive fertilizer use can lead to soil acidification, nutrient imbalances, and environmental pollution. Therefore, there is a need to develop sustainable nutrient management practices that not only ensure optimal crop growth and yield but also maintain soil health and minimize environmental impacts. Overall, future research should focus on developing innovative and sustainable nutrient management strategies that optimize nutrient use efficiency, minimize environmental impacts, and ensure the long-term sustainability of paddy crop production.

4. CONCLUSIONS

This SLR discusses the challenges and limitations of nutrient deficiency management in paddy crop production across different growth stages. The authors point out that nutrient management is crucial for optimal growth and yield of paddy crops, and deficiencies can lead to stunted growth, reduced yield, and poor grain quality. This SLR highlights the importance of macronutrients like nitrogen, phosphorus, potassium, sulfur, calcium, and magnesium, along with micronutrients like iron, manganese, copper, zinc, boron and silicon. Effective nutrient management practices like fertilization, foliar spraying, and breeding for nutrient-use efficiency can help mitigate nutrient deficiencies and improve crop growth and yield. This SLR provides a comprehensive overview of the current state of nutrient deficiency management in paddy crop production. However, the review could have provided more specific recommendations on the optimal levels of macronutrients and micronutrients at different growth stages to achieve optimal growth and yield.

Future research directions in the field of nutrient management for paddy crop production may include investigating the potential of emerging technologies such as precision agriculture, remote sensing, and artificial intelligence for optimizing nutrient management. These technologies can assist farmers in applying the optimal quantity of nutrients at the optimal time, thereby enhancing crop growth and yield. Additionally, research could focus on developing new nutrient management practices that are environmentally sustainable, cost-effective, and easy to implement for small-scale farmers. Overall, this SLR provides valuable insights into the challenges and opportunities in nutrient management for paddy crop production.

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