

Fertilizer Management: Impact on Plant Growth, Productivity, and Phytochemical Composition

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Abstract: Management of fertilizers influences plant growth, productivity of crops, quality of soil and biosynthesis of phytochemicals. The aim of this review is to examine effects of mineral fertilizers, organic manures, biofertilizers, and INM on plant physiology, yield, efficiency of nutrient utilization and biochemical makeup. Of special interest is the effect of nitrogen, phosphorus, potassium, and sulfur on primary metabolic pathways, photosynthesis, transfer of energy, enzyme activity, and biosynthesis of secondary metabolites. This review focuses on the influence of fertilizer management on plant secondary metabolism, which affects the accumulation of phenolic compounds, flavonoids, alkaloids, terpenoids, steroids, essential oils and other bioactive phytochemicals. Literature data from cereal, vegetable, horticultural, aromatic and medicinal plants show that balanced nutrition enhances growth and productivity and affects the quality of the products in terms of their biochemical composition. Organic and biofertilizer contribute to soil fertility and nutrient availability, while INM uses rapid action of mineral fertilizers in conjunction with organic and biological components. The review further elaborates on the role of precision nutrient management and nano-fertilizer technology and its capacity to enhance nutrient use efficiency and decrease environmental losses of nutrients. However, despite the progress in these areas, species-specific effects, agro-ecological variability, and the existence of trade-offs between yield and phytochemical production constitute a significant challenge. Future research should be devoted to site-specific nutrient management, biostimulants based on microorganisms, controlled release of nutrients, and quality-oriented fertilizer management. In general, sustainable fertilizer management constitutes a crucial tool for sustainable agriculture development.

Keywords: Fertilizers; plant growth; crop productivity; biofertilizers; phytochemicals; soil health, etc.

I. INTRODUCTION

Fertilizer management is considered to be one of the key components influencing plant development, yields, and biochemical composition [1], [4]. Over the past decades, intensive agricultural systems have been utilizing mineral nutrients necessary for conducting vital processes, including photosynthesis, respiration, protein synthesis, nucleic acid metabolism, enzymes, and cell development [46], [64]. Nitrogen, phosphorus, and potassium are needed in larger amounts and form the basis of plant nutrition [4], [29]. Currently, however, there is a need to increase productivity for growing populations and reduce environmental impact of fertilizer application [2], [43].

In addition to biomass and productivity, it is becoming increasingly evident the impact that fertilizers have on regulating the synthesis of secondary metabolites in plants, popularly called phytochemicals. Secondary metabolites like phenolic acids, flavonoids, tannins, alkaloids, terpenoids, and steroids are essential in ensuring proper defence mechanisms and environmental adaptation of the plants in addition to their nutritional value [7], [27], [28]. Current research shows that the kind of fertilizer and the rate of fertilization affect the partitioning of carbon into primary and



secondary metabolic pathways in order to enhance the biological activity of crops [30], [55]. As such, sustainable fertilization practices need to consider both yield and biochemical quality improvement and soil health maintenance.

II. METHODS AND APPROACHES TO NUTRIENT MANAGEMENT

Modern nutrient management uses an extensive variety of inputs designed specifically for certain soil-crop systems. This may involve conventional use of fertilizers, more complex approaches based on site-specific modeling or biological approaches.

2.1 Mineral and Conventional Fertilization

Mineral fertilizers constitute the major source of easily available forms of nitrogen, phosphorus and potassium in world agriculture. They include urea (46% N), diammonium phosphate (DAP), single superphosphate (SSP) and muriate of potash (MOP) [1], [11], [47], [59]. For cereals like wheat and maize, the use of nitrogen fertilizers is usually increased to 50–150% of the recommended amount [13], [29]. For example, recommended rates of nitrogen, phosphorus and potassium (NPK): 180:60:30 kg ha⁻¹ for hybrid maize increase the concentration of crude proteins and nutrients' uptake by grains and straw [29]. Excessive use of mineral fertilizers may lead to soil acidification, decrease of soil microbial biomass, and lower NUE [2], [19].

2.2 Soil Test Crop Response (STCR) Approach

The Soil Test-Crop Response (STCR) technique is a site-specific nutrient management system which makes use of soil testing for application of customized fertilizer doses for certain yield targets [9], [38]. The STCR model takes into consideration the nutrient supplying capability of the soil along with the nutrient needs of the crop, thereby improving fertilizer utilization efficiency. In the case of coriander production, the application of STCR through integrated nutrient management led to 56.9% improvement in green foliage yield along with an increase in the concentration of total phenolic and flavonoids content [9]. Similar results were also observed in green gram [38].

2.3 Bio-Organo-Chemical Systems

Bio-Organo-Chemical fertilizers are a new sustainable agricultural practice where mineral fertilizer components are mixed with organic residues and bio-fertilizers [23]. The purpose of these practices is to combine the quick nutrient supply from chemical fertilizers with the long-term impact of organic residues and the biological activities of PGPM. For instance, in the case of sweet marjoram, the use of 50% recommended chemical fertilizer plus 50% of natural rocks (feldspar and rock phosphate) together with bio-fertilizers enhanced the height of plants, herbal mass production, and percentages of essential oil production [23].

III. PHYSIOLOGICAL AND BIOCHEMICAL ROLES OF MACRONUTRIENTS

The major macronutrients (N, P, K) and secondary nutrients such as Sulfur (S) are important in physiological and biochemical roles.

3.1 Nitrogen (N) and Primary Metabolism

Nitrogen is an essential component of amino acids, proteins, enzymes, nucleic acids, and the chlorophyll pigment [4], [64]. It is the most important element in relation to vegetative growth and leaf area expansion. Adequate nitrogen supply ensures enhanced photosynthesis and biomass production through the maintenance of high concentration of Rubisco and other photosynthetic enzymes [4]. In rice, adequate nitrogen supply improves plant height, tillering capacity, and spikelet number per panicle [1]. Biologically, nitrogen plays roles in electron transport, hormone control, and coordination between carbon and nitrogen metabolism [4], [63]. But nitrogen availability determines the tradeoff between primary and secondary metabolism. Nitrogen deficiency results in a metabolic switch, leading to increase in the level of secondary metabolites like phenolics due to the diversion of carbon from protein synthesis to shikimic acid pathway [55].

3.2 Phosphorus (P) and Energy Metabolism

Phosphorus is required for the formation of adenosine triphosphate (ATP), the cell's energy carrier, and is an important constituent of phospholipids present in the membranes of cells and nucleic acids [4], [46]. Phosphorus is highly



important in root initiation, early flowering and seed formation [1], [4]. Phosphorus fertilization, in particular, when combined with phosphate-solubilizing bacteria (PSB), has been found to increase the biomass and the phosphorus-use efficiency in chickpea [18]. Phosphate-solubilizing bacteria increase the availability of phosphorus by mineralizing organic phosphorus and solubilization of inorganic phosphates by the production of organic acids such as gluconic acid, thus reducing the pH of soil [6], [15].

3.3 Potassium (K) and Enzyme Activation

Unlike other macronutrients, potassium does not form any part of the structural organic compounds. Potassium is an essential osmoticum and an activator of more than 60 enzymes responsible for photosynthesis, protein formation, and carbohydrate metabolism [4], [12], [46]. It controls stomatal function, water absorption, and movement of photosynthates from source to sink [4], [44]. Potassium use in maize crops has been shown to increase the ability of the plants to withstand water stress conditions and regulate stomata [4], [44]. Tea plantations have also shown by metabolomics analysis that although high K hinders the accumulation of amino acids, it promotes the metabolism of flavonoids [30].

3.4 Secondary Macronutrients: Sulphur

Sulphur has been increasingly seen as a very important nutrient for yield and quality, especially for oil seeds and legumes since sulphur is essential for the production of sulfur containing amino acids such as cysteine and methionine. Application of 40kg/ha of S has been shown to increase significantly the yield and uptake of nitrogen, phosphorous, potassium, and micronutrients like Fe, Mn, Zn, and Cu in green gram [16]. Sulphur fertilizer increases the synthesis of vitamins and glycosides in different plants [16], [27].

IV. ORGANIC AND BIOLOGICAL FERTILIZER OPTIONS

The adoption of eco-friendliness in agriculture requires the use of organic fertilizers and the “microbial wealth” of the soil for sustenance.

4.1 Organic Manures and Soil Physical Health

The use of organic manures such as farmyard manure (FYM), vermicompost, poultry manure, and oil palm residue enhances soil fertility via stimulation of soil microbial biomass, besides improving soil physical characteristics such as bulk density, water retention, and structural properties [6], [14], [21]. In case of vegetable based agroecosystems, the use of FYM along with mineral fertilizers reported higher root-mass and root volume densities in cauliflower and capsicum [8]. It has been found that poultry manure up to 10 t ha⁻¹ gives better bulb yield in onion [12]. Moreover, the green manures such as *Mucuna cinerea* play an important role in producing dry matter and nutrient uptake via mineralization of organic matter [20].

4.2 Biofertilizers and PGPRs

Biofertilizers are made up of live microorganisms that aid plant growth in different ways such as biological N fixation (*Azotobacter*, *Rhizobium*), phosphate solubilization (*Pseudomonas*, *Bacillus*), and the production of siderophores and phytohormones such as auxins and gibberellins [12], [25], [66]. In red cabbage, the use of *Trichoderma harzianum* and *Pseudomonas fluorescens* as biopriming treatment along with 75% mineral fertilizer application improved macronutrient nutrition and root growth [15]. Likewise, in lettuce, vermicompost and PSB showed the highest productivity (27.5 t ha⁻¹) than any other inorganic fertilizer application [5]. Arbuscular mycorrhizal fungi (AMF) are also very important for P absorption and drought and salinity tolerance of plants [35], [53].

V. INTEGRATED NUTRIENT MANAGEMENT (INM) AND SUSTAINABLE PRODUCTIVITY

Integrated Nutrient Management (INM) entails the integration of mineral fertilizers, organic manures, and bio-fertilizers for sustaining productivity without compromising the soil [1], [36].

5.1 Synergistic Effects on Crop Yield and Quality

The integrated nutrient management practices produce better yields as compared to chemical fertilizers alone. The rice-rice cropping systems using the integrated application of 100% NPK and FYM have led to the production of better



grain yields (up to 8023 kg/ha) and soil organic carbon [21]. For onions, the implementation of integrated nutrient management practices leads to the production of 22% to 34.1% increased bulb yield and improved the health-promoting sulfur content and quercetin in them [12], [27]. For arecanut-based cropping systems, the application of bio-fertilizer consortium along with organic recycling and 75% NPK has been observed to maximize the system productivity [3], [17].

5.2 Increased efficiency in nutrient use and economics

The INM system increases NUE as it ensures that nutrients are released in sync with the needs of the plant and minimizes environmental losses like leaching and volatilization [2], [22]. For example, in case of integrated management in maize, there was nitrogen use efficiency of 58.7% which was much higher than sole application of chemicals [2]. Economically speaking, an INM system often leads to increased profits because of reduced need for costly mineral fertilizers and continuous yield [15], [25], [39].

VI. EFFECT ON PHYTOCHEMISTRY AND SECONDARY METABOLISM

The chemistry of the plants is extremely dependent on the form of the nutrient supplied and its availability rate.

6.1 Phenols, Flavonoids, and Antioxidant Capacity

6.1 Phenols, Flavonoids, and Antioxidants Capacity

The availability of nutrients plays an important role in the formation of phenolics and flavonoids, which are key antioxidants in various plants. It was found that the use of vermicompost and NPK increased phenolic compounds and flavonoids and improved the capacity of DPPH-scavenging activity in medic savory (*Satureja macrantha*) [7]. For tea, it was found that a high level of P and K fertilizer application stimulates the metabolic pathway of flavonoids and suppresses amino acid content [30]. The same was reported for *Origanum dictamnus*, where polysaccharide-based INM system increased the antioxidants capacity and antimicrobial properties of the plant [32].

6.2 Essential Oils and Volatile Compounds

In the case of aromatic plants, fertilizer management is critical to the production of essential oil (EO). In *Mentha piperita*, the use of green manure intercropping (50% *Vicia villosa* + 50% *Hordeum vulgare*) resulted in the highest menthol (37.73%) and 1,8-cineole (7.78%) concentrations [28]. Organic manures and inorganic fertilizers greatly impacted the yields and quality of herb and oil production in French basil [40]. For sweet marjoram, bio-organico-chemical fertilization contributed to the increase of percentages of 36 different EO components such as β -pinene and γ -terpinene [23]. Also, microbial consortia were proven to elevate aromatics in *Ocimum tenuiflorum* [54].

6.3 Alkaloids and Other Metabolites

The accumulation of bioactive metabolites including alkaloids is also nutrient dependent. In *Anisodus tanguticus*, the exogenous manipulation of macroelements was found to promote alkaloid accumulation [34]. For *Gloriosa superba*, the INM techniques proved to be efficient in increasing growth and biochemical parameters including colchicine concentration [10]. In milk thistle (*Silybum marianum*), the type of fertilization and plant genotype both had a significant impact on flavonolignan seed content [42]. In medicinal cannabis, the addition of N, P, K, and humic acid significantly modulated the chemical composition [41].

VII. CASE STUDIES IN IMPORTANT CROPS

7.1 Rice (*Oryza sativa* L.)

Rice is the main food for about 50% of the world's population. Application of fertilizer in rice includes the optimization of grain production while minimizing nitrogen loss. Application of recommended NPK increases the height of plants and panicle lengths; the increase in number of grains per panicle is between 23% and 48% [1]. The application of both 75% NPK and vermicompost/poultry manure has resulted in grain production of 6.16-6.27 tons/ha while increasing carbon sequestration [6]. Long-term application of fertilizers in the rice-rice system reveals that the application of FYM along with NPK maintains the soil fertility and productivity [19], [21]. Also, nano-DAP and nano-urea are gaining importance as technologies used to optimize gas exchange properties and improve NUE in the paddy field [47], [50].



7.2 Wheat (*Triticum aestivum* L.)

Productivity in wheat is strongly influenced by the nitrogen schedule and overall management. It was proven that the 75% RDF along with vermicompost and PSB increases the growth rate and NPK content [25]. Using biofertilizers such as *Azotobacter* and *Azospirillum* in wheat positively influences the soil nitrogen content and crop yield [22], [37]. Furthermore, the nitrogen fertilization schedules in wheat affect phenolic content and the antioxidant capacity of the grains and following sprouts [51], [52].

7.3 Maize (*Zea mays* L.)

Maize is a nutrient-demanding plant. The importance of balanced K fertilization in the closure of yield gaps and the improvement of maize resistance has been emphasized in the studies done in China and India [44], [45]. Application of 100% RDF with vermicompost and *Azospirillum* increases the productivity of hybrid maize and protein content [25]. In the trans-gangetic plains, nitrogen management has been successfully used to increase the efficiency of maize and soil health [61].

7.4 Horticultural and Medicinal Crops

INM in onions (*Allium cepa*) increases yield by 34% along with improving nutritional quality [12], [27]. In strawberries, nano urea in combination with *Azotobacter* contributes to the quality improvement and biochemistry parameters [24]. In medicinal crops like *Murraya paniculata*, leaf potassium concentration was positively correlated with leaf dry weight but negatively associated with total flavonoids concentration, meaning that the excessive amount of potassium favors biomass production instead of secondary metabolites [26].

VIII. ENVIRONMENTAL IMPACTS AND NUTRIENT USE EFFICIENCY

Environmental sustainability of agricultural practices is directly associated with fertilizer application.

8.1 Soil Health and Microbial Diversity

Sole usage of chemical fertilizers results in soil acidification and decreased microbial activity, whereas organic and integrated fertilizer management provides the maintenance of soil fertility through increased organic carbon content and enzymes activity [2], [19]. Integrated management practices in rice contribute to soil organic carbon and carbon sequestration, thus helping to mitigate the effects of climate change [6]. Moreover, the use of organic material contributes to decreasing soil bulk density and improved soil structure [6], [21].

8.2 Leaching and Greenhouse Gas Emissions

Over-application of nitrogen leads to nitrate leaching into the ground water and emission of nitrous oxide to the atmosphere. Research on maize indicates that chemical fertilization leads to greater nitrate leaching (32.4 mg/L) when compared to organic and integrated fertilization [2]. Improved NUE through integrated fertilizer systems helps in reducing such environmental loss [2], [57]. Application of value-added fertilizers and appropriate fertilization strategy helps in minimizing ammonia volatilization loss [31], [57].

IX. PRECISION AND NANO FERTILIZER TECHNOLOGY

Nanotechnology and Precision Agriculture technologies lead the way in achieving better nutrient management.

9.1 Efficiency of Nano Fertilizers

Nano fertilizers such as nano urea and nano-DAP, which offer large surface area and targeted delivery, may replace conventional mineral fertilizers. In strawberries, nano urea resulted in improved qualitative and biochemical characteristics of plants, where low doses of nitrogen could be used [24]. In rice, nano-DAP has been found to improve yield through modulation of gas exchange traits and increased P use efficiency [47]. Further nanohybrid coating of fertilizers and use of nanobubbles in irrigation water are being researched to develop sustainable nutrient delivery systems that induce nutrient uptakes genes [60], [62].



9.2 Precision Management Tools

Precision nitrogen management utilizes vegetation indices and site-specific nutrient experts to balance supply and demand [50], [58]. The precision tools contribute in reducing yield gap and environmental impacts, particularly in intensive irrigation zones [48], [58].

X. LIMITATIONS AND RESEARCH GAPS

Despite advantages of different fertilization approaches, there are still a number of issues related to fertilizer research.

- **Species-Specific Responses:** The response to fertilizers varies considerably between species and genotypes, which makes it hard to give recommendations [28], [42], [55].
- **Yield versus Quality:** Usually, there is a compromise between the quantity of plants obtained using certain fertilization strategy and their phytochemical concentration [26].
- **Agro-Ecological Differences:** Most of the research is site-specific and the effectiveness of integrated fertilization systems can be influenced by soil and climatic characteristics [8], [65].
- **Long-term Impact:** More multi-decadal researches are required to identify the effect of fertilization strategies on soil microbial resilience and nutrient cycle stability [19], [21].

XI. FUTURE DIRECTIONS

Future research must revolve around the connection between sustainability and high-quality crop production.

- **Microbial Engineering:** The potential of soil microbes can be exploited using microbial consortia to promote plant secondary metabolites and tolerance against stress [56].
- **Synchrony of Release:** It will be important for developing fertilizers with release properties that synchronize with the nutrient requirements of crops so that NUE close to 100% is achieved [31].
- **Phytochemical Management:** In medicinal and aromatic plants, there should be a shift in management from being yield-oriented to quality-oriented by focusing on phytochemicals [28], [41].
- **Crop Management Techniques:** Microbial biostimulants, nano-coatings, and silicate potassium represent techniques to enhance the growth of plants under stress conditions [15], [49], [60].

XII. CONCLUSION

The management of fertilizers is an important component of sustainable agriculture that affects every single phase in the lives of plants right from their primary metabolism to their synthesis of different phytochemicals. While it is true that mineral fertilizers are indispensable for obtaining high yield, the combination of mineral fertilizers with organic manures and biofertilizers is very important to ensure soil health and sustainable environment. The INM is one of the most superior practices which not only results in high yield but also increases nutrient use efficiency along with enhancing biochemical quality of various food and medicinal crops.

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