Sufficiency of Natural Resources in Phosphorus Fertilizer Production and Sustainable Phosphorus Management Strategies in Agriculture

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***Abstract*—** Phosphorus is one of the most important macronutrients for plant growth and productivity. However, most of the phosphorus in the soil is found in insoluble forms and this makes it a limiting factor in plant production. The phosphorus needed by plants is met by using phosphorus fertilizers produced from phosphate rock mines found in limited regions and limited reserves in nature. It is expected that the shortage of natural resources for phosphorus fertilizer production will be one of the major problems to be overcome in the next century. In this article, the status of available phosphate reserves in the world for phosphorus fertilizer production and sustainable phosphorus management strategies in crop production are evaluated.

***Keywords*—** Phosphorus Fertilizer, Natural Sources, Management Strategies**.**

I. Introduction

Phosphorus (P) is one of the three most important plant nutrients along with nitrogen (N) and potassium (K). Phosphorus is a vital macro element in plant nutrition and plays a central role in metabolic processes such as photosynthesis, respiration, energy transfer and cell division [1]. It is absolutely necessary especially in processes such as plant root development, flowering and fruit formation [2]. Phosphorus fertilizers are of great importance for the sustainability of agricultural production. Phosphorus fertilizer applications in agricultural production directly affect plant productivity by increasing the natural phosphorus capacity of the soil. The amount of phosphorus in the soil is usually insufficient in cultivated soils and this becomes a limiting factor in yield. Therefore, fertilizers containing phosphorus are widely used in agricultural production.

Since most of the phosphorus in soils is present as organic compounds or insoluble inorganic forms, direct uptake by plants is limited [2]. Although phosphorus is an indispensable macronutrient for plant growth, most of the phosphorus applied to soils cannot be taken up directly by plants due to its transformation into insoluble and useless compounds as a result of chemical and biological processes in the soil. Only 10-30% of the applied phosphorus fertilizers can be taken up by plants, while the remaining part is retained in the soil in various ways and becomes useless [3].

Since phosphorus in soils is usually found in forms that are difficult to be taken up by plants, fertilization is a necessity. The limited availability of phosphorus resources worldwide has made phosphorus management a strategic issue for agricultural sustainability in the long term. Increasing phosphorus utilization efficiency, reducing losses and developing recovery methods are among the current research topics [4].

In this article, the importance of phosphorus fertilizer production, current production status in the world, adequacy of natural phosphate resources and potential problems encountered in production are discussed.

II. The Role of Phosphorus in Plant Physiology

Phosphorus is involved in the structure of energy carrier molecules such as ATP (adenosine triphosphate) and ADP (adenosine diphosphate) in biological metabolism. These molecules are involved in many vital events such as cell division, growth and substance transport [5]. Phosphorus promotes root development, especially in young plants. A strong root system increases plant resilience by increasing water and nutrient uptake. Phosphorus requirement is also high during flowering and seed formation processes. Phosphorus supports chlorophyll synthesis and is involved in carbon metabolism. It is also involved in intracellular signal transduction and membrane phospholipids [6]. Phosphorus deficiency in soil is manifested by symptoms such as purple-red foliage, stunted growth and late ripening, especially in young plants. Phosphorus deficiency can seriously reduce crop yield by affecting the development of generative organs such as flowers, fruits and seeds [7].

III. Uses of Phosphate Rock

Phosphate rock is a mineral source containing phosphorus and is an important raw material used in various industries, especially in fertilizer production. Approximately 50% of the world phosphate rock production is converted into phosphoric acid and this acid is used in the production of high quality fertilizers by reacting with ammonia [8]. The biggest consumption area of phosphate rock is the agricultural sector. Phosphorus is an essential nutrient for plant growth and phosphate fertilizers produced from phosphate rock (e.g. diammonium phosphate, triple superphosphate) are used extensively. In addition, the chemical industry produces phosphoric acid, detergents, animal feed additives and other phosphorus-based products from phosphate rock. In addition, phosphate rock can contain rare earth elements and these elements are also utilised in the high-tech industry.

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IV. Global Phosphate Rock Reserves and Future Sufficiency

Phosphate rock consumption worldwide is shaped by population growth, agricultural sector and demand for phosphorus-based chemical products. The prominent countries in terms of phosphate rock reserves and their reserve amounts are as follows [9]:

- Morocco and Western Sahara: 50 billion tonnes (approximately 70% of world reserves)
- Egypt: 2.8 billion tonnes
- Tunisia: 2.5 billion tonnes
- Algeria: 2.2 billion tonnes
- China: 1.9 billion tonnes
- Brazil: 1.6 billion tonnes
- South Africa: 1.6 billion tonnes
- Saudi Arabia: 1.4 billion tonnes
- Australia: 1.1 billion tonnes
- Finland: 1 billion tonnes
- Jordan 1 billion tonnes
- USA: 1 billion tonnes
- Total world reserves: 72.000

More than 85 per cent of phosphate reserves are concentrated in just a few countries. Morocco and Western Sahara have more than 70 per cent of the world's reserves. The USA and Morocco are both major producers and exporters [9]. China is the world's largest producer and consumer of phosphate. India is the largest importer of phosphate fertilizers. Existing world reserves are critical for future global phosphate demand. Increasing demand for phosphate fertilizers increases the consumption of phosphate rock. China, USA and Russia are among the major producers of phosphorus fertilizers. The world's phosphate rock reserves are the main source of phosphorus, a critical raw material for the agricultural and industrial sectors. Phosphate rock resources worldwide are more than 300 billion tonnes and economically exploitable reserves are estimated at about 72 billion tonnes [9].

The annual worldwide need for phosphorus fertilizer is estimated to be approximately 46 million metric tonnes by 2023. The world demand for phosphorus fertilizer continues to increase as phosphorus plays a vital role in plant nutrition and the demand for food production increases with the growing global population [10]. Phosphorus is a non-renewable resource and the limitation of phosphate rock reserves poses serious risks for fertilizer security in the future. If the existing reserves are consumed at this rate, it is estimated that high grade reserves may be depleted within 50-100 years [4]. In addition, the unbalanced geopolitical distribution of phosphate resources and the fact that Morocco and Western Sahara hold about 70% of global reserves create a strategic dependence on phosphorus supply [11]. These data show that phosphorus fertilizer production is dependent on a limited number of countries and that phosphorus fertilizers have a fragile structure in terms of supply security.

V. Challenges in Phosphorus Fertilizer Management

A. Environmental Impacts

Excessive and irregular use of phosphorus fertilizers leads to environmental problems such as eutrophication (reduction of oxygen levels in water) [12]. It causes algae blooms and ecosystem imbalances in water bodies.

B. Economic and Political Risks

Phosphorus rock reserves are non-renewable and the dependence of phosphate rock production and exports on a few countries causes price fluctuations, political instability and security of supply issues, putting phosphorus security at risk. For example, in 2008, worldwide phosphate fertilizer prices tripled over the previous year.

C. Inefficient Use

Most of the phosphorus applied to the soil is rendered useless by various physicochemical processes. These processes include pH imbalances, precipitation with metal ions, adsorption, microbial competition and low organic matter level. Since phosphorus in soil tends to bind, the rate of phosphorus available to plants is low. Only 15-30% of the applied phosphorus can be utilised by plants [13]. The main factors limiting phosphorus availability are as follows:

Soil Reaction

Soil pH directly affects the solubility of phosphorus. In acidic soils (pH < 5.5), phosphorus reacts with Fe^{3+} and Al^{3+} ions to insoluble iron and aluminium phosphates. In alkaline soils (pH > 7.5), phosphorus combines with Ca^{2+} ions to form calcium phosphate (Ca-P) compounds [2]. Optimal phosphorus uptake usually occurs in the pH 6.0-7.0 range.

Fixation of Phosphorus

Phosphorus becomes fixed by adsorbing to soil colloids or precipitating with minerals. Clay minerals, especially minerals with high surface area such as kaolinite and smectite, bind phosphorus to their surfaces and reduce its availability [14].

Insufficiency of Organic Matter and Microbial Activity: Insufficient organic matter in the soil makes it difficult for phosphorus to remain soluble. In addition, some microorganisms (e.g. microbial biomass) may compete with the plant by retaining phosphorus in their own bodies [15].

Phosphorus Form and Application Method:

The type of phosphorus applied (e.g. superphosphate, diammonium phosphate) and its distribution in the soil also affect the uptake. Since phosphorus is not mobile in the soil, phosphorus uptake in the soil often decreases with non-local application methods (sprinkling), while uptake increases with local application methods (e.g. banded fertilisation) [16].

Liming and Calcium Effect:

Liming processes carried out to increase the pH of the soil may cause phosphorus to become insoluble by binding with Ca, especially in the presence of $CaCO_3$ [17]. This limits the availability of phosphorus, especially in calcareous soils.

VI. Sustainable Practices and Innovations in Phosphorus Fertilizer Management

Phosphorus is a vital nutrient for plant growth and an essential component of sustainable agriculture. Efficient phosphorus fertilizer management ensures optimum crop production while minimising environmental impacts, maintaining soil health and conserving non-renewable phosphorus resources. Some sustainable phosphorus management practices are summarised below:

A. Soil Testing and Fertilizer Needs Assessment

It is essential to conduct regular soil tests to determine phosphorus levels in the soil and the specific nutrient requirements of the crop. Specific application prevents overuse and reduces runoff that can lead to eutrophication of water sources, and the efficiency with which plants utilise phosphorus is increased.

B. 4R Adoption of Nutrient Management

The basic fertilisation techniques of right source (use the appropriate type of phosphorus fertilizer), right rate (apply the right amount according to crop needs and soil tests), right time (adjust application according to crop growth stages to maximise phosphorus uptake) and right location (apply fertilizer in a way that minimises runoff and leaching) should be followed.

C. Precise Application Methods

Application of phosphorus fertilizers exactly where and when the crops need them reduces losses and increases utilisation efficiency. Therefore, balanced and timely fertilisation is important [3]. Techniques such as banding (placement of fertilizer close to the seed) and fertigation (delivery of nutrients through irrigation) are effective. Microdosing, controlled-release fertilizers, plant-specific applications and targeted fertilization techniques should be promoted.

D. Improved Fertilizer Formulations

Advanced efficient fertilizers with coatings or inhibitors reduce soil fixation and leaching losses and increase phosphorus availability. Nano fertilizers and controlled release formulations are promising technologies.

E. Integration of Organic and Inorganic Sources

Combining organic materials (e.g. manure, compost) with inorganic fertilizers improves soil fertility and provides a slow-release source of phosphorus. Organic sources also contribute to long-term sustainability by improving soil structure and microbial activity. Organic materials (compost, farmyard manure) can both improve soil structure and increase the solubility of phosphorus. These methods are particularly important for sustainable agricultural systems.

F. Increasing Phosphorus Utilisation Efficiency

Crop rotation, intercropping and the use of phosphorus efficient crop varieties can increase phosphorus utilisation. Phosphate solubilising microorganisms (e.g. Bacillus, Pseudomonas) and mycorrhizal fungi (especially arbuscular mycorrhizae) mobilise insoluble phosphorus in soil and make it available to plants [18].

G. Minimising Environmental Impacts

Avoiding excessive use of phosphorus fertilizers prevents runoff into water bodies that can cause algal blooms and eutrophication. Buffer strips and cover crops near water bodies can capture and recycle phosphorus from agricultural fields.

H. Recycling

Recovery systems should be established from wastewater and animal wastes, and phosphorus recovery should be provided by composting from organic wastes.

I. Policy and Education

Educating farmers on best practices and providing subsidies for soil testing and precision technologies encourage sustainable use. Policies promoting phosphorus recycling and research on alternatives to mineral phosphorus are important

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