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Review Paper

Role of Minjingu Rock Phosphate and Nitrogen Fertilizer in Improving Phosphorus and Nitrogen Use Efficiency in Maize: A Kenyan Case Study

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ABSTRACT

Maize, an essential food item in Kenya, is grown in soils characterized by low pH and low plant-available phosphorus (P), particularly in the Western part of the nation. Low available P and soil acidity are the fundamental causes of low soil fertility in many cropped soils. Such farms are also characterized by low soil nitrogen (N) and inadequate use of inputs such as mineral fertilizers. Deficient use of agronomic inputs, especially phosphorus and nitrogen, has not only led to low yields but also has resulted in poor product quality in terms of nutritional content and yield, in addition to soil fertility degradation. Enhanced use efficiency and access to nitrate fertilizers and soil amendments such as MRP and lime will be most crucial to improving growth, grain yield, nutritional quality, and economic returns, thus reducing poverty and hunger as well as improving good health in the country.

HIGHLIGHTS

- Maize is an essential food item in sun Saharan Africa grown in soils that have become increasingly deficient in major plant nutrients such as N and P that has primarily influenced the crop's grain yield, nutritional quality, and economic returns.
- N plays a key role in crops' plant chlorophyll formation, growth and development and grain productivity, and nutritional quality.
- P plays a significant part in plant development and nutrition, and it is responsible for the transport of energy for the production of organic compounds and the promotion of root growth and development in plants.
- Improving P and N use efficiency is essential in reducing fertilizer costs, ensuring high grain yield and economic benefits at harvest, and minimizing environmental-related impacts caused by volatilization, surface run-off, leaching, and microbial immobilization.
- Minjingu Rock Phosphate remains a cheap and sustainable soil amendment that reduces P fixation and Al toxicities, thus increasing P availability and uptake compared to inorganic fertilizers

Keywords: Maize, Phosphorus use efficiency, nitrogen use efficiency, Yield

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Maize which is a basic food item in Kenya is grown in soils characterized by low pH (Nyoro *et al*. 2004; Gitari *et al*. 2015; Nduwimana *et al*. 2020) with low plant-available phosphorus (P), particularly in Western parts of the country (Okalebo, 2009; Kisinyo *et al*. 2009). Acid soils, therefore, are generally infertile with poor plant growth caused by one or more interacting factors such as the buildup of manganese (Mn) or aluminum (Al) toxicities. The factors have adverse effects on soil microbial activities and many nutrient deficiencies, for instance, phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), and molybdenum (Mo) (Gudu *et al*. 2005; Hassan *et al*. 2020; Ngugi *et al*. 2022). Due to low and declining fertility, maize (grain) yield has stagnated at an average of 2 t ha^{-1}, a value below the attainable 6 t ha^{-1} (Sanchez, 1997; Kang'ethe, 2004; Ochieng' *et al*. 2021).

Poor crop growth due to P deficiency results in poor quality products, low quantity yields, and low economic returns, a circumstance that results in food shortages, recurrent hunger, malnutrition crisis, and eventually loss of lives (Nekesa *et al*. 2011; Nyawade *et al*. 2020; Mwakidoshi *et al*. 2021). P is the second most limiting nutrient in crop production after N (Khan *et al*. 2018; Guignard *et al*. 2017) and an essential nutrient in crop production (Marschner, 1995; Gitari *et al*. 2020), and its application to soils is essential to achieve maximum crop yield.

Nitrogen is the most significant yield and quality-restricting nutrient in crop production globally, with its management being one of the most critical aspects required for improving N use efficiency (Gitari *et al*. 2018). The inefficient use of nitrogen contributes to its huge losses to the environment by processes such as volatilization, surface run-off, leaching, and microbial immobilization (Sun *et al*. 2013; Nyawade *et al*. 2019). In Kenya, the average yield for rain-fed maize between 2007 and 2016 fell < 2.0 t ha^{-1} (FAOSTAT, 2018). Sanchez (2015) reported reduced soil fertility, mainly attributed to continuous cropping, without nutrient replenishment programs, as one of the main limitations to optimum crop production among the smallholder farmers. The current nutrient use estimates are still very low, with most farmers applying a total of < 10 kg of P, N, and K inputs, in both organic minerals and chemical fertilizer sources, as reported by Korir *et al*. (2017). Most Kenyan farmers have completely no or very little practice of restocking the nutrients from the harvested crops, probably due to resource constraints or ignorance (Gitari *et al*. 2019). Therefore, soils have become increasingly deficient in major plant nutrients and particularly N (Karki, 2002). According to Adediran and Banjoko (1995), nitrogen is a critical plant nutrient that largely influences yield; thus, it is key in maize production. Deficient use of agronomic inputs, especially nitrogen, has not only led to low yields but has also resulted in poor grain quality in terms of nutritional content and decreased economic returns, in addition to soil fertility degradation. Enhanced use efficiency and access to nitrogen fertilizer will be most crucial to reducing poverty and hunger as well as improving good health in the region as stipulated in the Sustainable Development Goals (Campbell *et al*. 2018). Therefore, there is a need to replenish and amend soils in Kenya to increase N and P availability and use in soils which will eventually improve maize productivity, nutritional quality, and economic benefits per unit area.

General information about maize

Maize (*Zea mays* L.) is believed to have originated from Mexico and Central America. Global figures indicate that over 200 million tons of maize are produced annually – rating the highest of the major staple cereals (FAOSTAT, 2018). Furthermore, maize is a vital source of essential minerals and vitamins for the human body. It provides ≥ 20% of total human dietary calories, as reported by Shiferaw *et al*. (2011). According to Prasanna (2014), developed countries currently uses less maize compared to the developing nations, with projection showing that the developing countries will develop a double demand for maize by the year 2050.

Maize (*Zea mays)* which is an essential food item in Kenya, is grown in soils characterized by low pH (Nyoro *et al*. 2004; Gitari *et al*. 2015; Nduwimana *et al*. 2020) with low plant-available phosphorus (P), particularly in Western Kenya (Okalebo, 2009; Kisinyo *et al*. 2009. It grows well and is better adapted to diverse agro-ecologies. It has claimed global significance due to its adaptable uses. For example, it can be used as livestock feed, human food, and as an essential component for various industrial goods.

Role of nitrogen and phosphorus in maize crop

Nitrogen is among the most crucial nutrients in both natural and agronomic ecosystems (Krivtsov *et al*. 2011). It is the most critical fertilizer nutrient for maize production and the most commonly limiting plant growth and development (Hart *et al*. 2009; Mwadalu *et al*. 2022). Increased N input influences growth rates, photosynthetic rates, and general plant quality and productivity (Bai *et al*. 2010; Maitra *et al*. 2021; Sousa *et al*. 2022). Poor soil nutrient management is a significant contributor to the decline of maize productivity in Kenya. Nitrogen deficiency is the primary constraint in maize production, according to Asghar *et al*. (2010). An adequate quantity of nitrogen during the active growth is paramount for optimum maize production. This is because it plays a crucial role in plant chlorophyll formation and grain productivity (Nasar *et al*. 2021).

Leaves are the primary organs for photosynthesis, accounting for ≥ 95% of the total photosynthetic processes in maize crops, with optimum maize crop yield and grain protein content being a function of several eco-physiological variables (Portes and Melo, 2014).

Similar positive effects of timely nitrogen supply on seed protein content were reported by Tollenaar (1977), who observed improved seed protein content as a function of the plant's timely physiological N condition, especially during flowering phases. These observations, moreover, agree with those of other scholars who reported that a timely and adequate supply of inorganic nitrogen often improved seed protein content since N is a primary constituent of protein (Tisdale *et al*. 1990; Iqbal *et al*. 2002).

Phosphorus is an essential nutrient in crop production (Marschner, 1995) and its application to soils is essential to achieving maximum crop yield. It plays a significant part in plant development and nutrition, and it is responsible for the transport of energy for the production of organic compounds (Marschner, 1995; Lollato *et al*. 2019). The element is also vital in promoting plant root growth and development (Zhang *et al*. 2016; Sulieman and Tran, 2015).

Total N uptake and plant N use efficiency

More NH_4^+ is probably readily adsorbed at the soil exchange complex unlike NO_3^- hence became available for plants uptake whereas NO_3^- N might have been prone to losses either via leaching in the clay minerals or by erosion due to run-off, courtesy of the relatively high rainfall during the period. (Ochieng *et al*. 2021). Furthermore, ammonium nutrition, unlike treatment with nitrate, is often associated with stimulation of lateral root branching resulting in high root density; this consequently enhances uptake of more ammonium than nitrates. Raven *et al*. (1992) reported that under poor soil aeration conditions, ammonium rather than nitrate becomes the most preferred N source for plant uptake with an increase in available physiological N (Cakmak *et al*. 2010).

Additionally, Amanullah (2016) reported higher N use efficiency (NUE) with ammonium Sulphate (AS) treatment over urea and calcium ammonium nitrate (CAN) and decreased NUE under low nitrogen rates. Low NUE under increased rates were associated with N-loses due to erosion, leaching, and surface run-off occasioned by high amounts of rainfall experienced during the study period. According to Fageria (2014), efficient utilization of N and crop genotypes are the primary determinants of the nitrogen harvest index (NHI). Finally, enhancement of protein content due to nitrate treatment was possibly attributed to improved N uptake and positive synergistic effects of nitrate with other essential divalent cations (like Zn and Ca) (Ochieng *et al*. 2021).

Timely nitrogen uptake promotes plant growth and increases the length and number of internodes, consequently increasing plant height (Koul, 1997; Chandler, 2015). Further, ammonium N gets lost easily through immobilization pathways to soil microbes (since soil microbes prefer ammonium to nitrate) and volatilization mainly under high temperatures. Further, hydrolysis of urea is often marked by forming an intermediate NH3 gas that is prone to volatilization leading to N- losses, which may have resulted in low plant heights due to N deficiency (Ochieng *et al*. 2021).

Effectiveness of nitrate and ammonium nutrition on NUE

Plants mainly take up nitrogen in three chemical forms: the positively charged ammonium (NH_4^+), negatively charged nitrate (NO_3^-), and the uncharged urea/carbamide, CO $(NH_2)_2$. Under aerobic conditions, where nitrification occurs, plants take N in the form of NO_3^- (Xu *et al*. 2012). However, in some cases, NH_4^+-N has been reported to predominate. Such environments include flooded grasslands (Jackson *et al*. 1989) and paddy rice fields (Ishii *et al*. 2011).

Nitrogen availability to plants greatly determines their growth rate and production potential. Plants use various forms of nitrogen in soils and inorganic forms, including ammonium, nitrate, and nitrite. Nitrate usually predominates in aerated soils, whereas ammonium nitrogen is more abundant in acidic/anaerobic soil environments (Miller and Cramer, 2004). On the other hand, nitrite availability varies globally depending on nitrification and denitrification balance. However, its soil concentration is generally inferior to that of ammonium and nitrate (Kotur *et al*. 2013).

Plants can take up organic nitrogen, whose primary sources comprise amino acids, urea, and peptides (Tegeder and Rentsch, 2010; Forde, 2013). In boreal ecosystems, the level of available amino acids to plants is usually similar to that of inorganic nitrogen (Näsholm *et al*. 2009). Normal plant growth can still be limited although nitrogen accessibility in natural ecosystems; hence plants have since developed signaling and transport strategies relative to their corresponding N- sources (Kiba and Krapp, 2016). Researchers have focused more on NO_3^- and NH_4^+ available N sources because they are often present in cropland and natural soils at high levels compared to the other N sources (Miller and Cramer, 2004). Despite nitrate being one of the nutrients, it also acts as a local systemic signal that usually regulates a genome's variety of gene expression and root morphology, leaf expansion, floral induction, and seed dormancy (Rahayu *et al*. 2005; Remans *et al*. 2006; Matakiadis *et al*. 2009; Castro *et al*. 2011; O'Brien *et al*. 2016).

Numerous responses by plants to nitrate nutrition are usually mediated via calcium and phytohormonal signaling pathways that include auxins, cytokinin, and abscisic acids, as Léran *et al*. (2015) and Krouk, 2016. Nitrate is usually converted to ammonium by nitrate reductase and nitrite- reductase (NiR), which often requires 8 moles of electrons per mole of nitrate. Therefore, the use of ammonium significantly lowers the energy demand to synthesize organic nitrogen compounds (Williams *et al*. 1987). Recent findings have reported that in the leaves of C3 plants, nitrate reduction is suppressed by elevated carbon dioxide (CO_2) while assimilation of ammonium is less affected (Bloom *et al*. 2010). Ammonium nitrogen, therefore, is a preferred nitrogen source in the future when global figures for CO_2 are projected to rise. Although in higher quantities, ammonium nutrition has been associated with detrimental effects on plant development (ammonium toxicity). Fertilization of plants with both ammonium and nitrate enhances plants' growth beyond the levels observable by treating plants with either of the sole nitrogen sources (Britto and Kronzucker, 2002). Previous reports have established that plants' response to nitrate can be affected by the co-provision of ammonium.

The interactions between NO_3^- and NH_4^+ should optimize nitrogen use in the soil where both forms are found at various concentrations within a short distance (Miller and Cramer, 2004). In addition, recent reports on the mechanisms of toxicity of excess ammonium Vis a Vis nitrate treatment have since been reported (Li *et al*. 2014; Esteban *et al*. 2016). Most plants benefit from a mixture of both N forms to enhance their synergy of nitrogen content as reported by (Miller and Cramer, 2004).

The net nitrogen influx via the roots consists of two main components: total nitrogen influx and total N efflux, as recorded in the study by Glass *et al*. (2002). In case the net N-influx is improved, that of total N-influx increases too, or the total N-efflux otherwise reduces. Specific nitrate and ammonium transporters often contribute to the total N-influx (Nacry *et al*. 2013), except high ammonium conditions (Esteban *et al*. 2016).

Generally, treating plants with ammonium nitrogen stimulates lateral root branching, while nitrate nutrition stimulates lateral root elongation. This suggests that fertilizing plants with nitrate and ammonium has a positive local synergistic impact on root development. Patterson *et al*. (2010) suggest that this complementarity reflects on an adaptation of lateral roots to the diverse mobilities observed with nitrate and ammonium.

Phosphorus availability, uptake, and use efficiency in maize

Maize responds to phosphorus (P) application significantly even at low rates of about 10 kg P $ha^{-1,}$ suggesting the need for adding the nutrient seasonally to soils to prevent not only its deficiency but also reinstate and improve soil productivity (Jama *et al.* 1997; Waigwa *et al.* 2002; Kisinyo *et al*. 2009). Through diffusion, P can move to the plant roots (Hinsinger *et al*. 2016; Trolove *et al*. 2003). This takes place (across the plasmalemma) when there is a variation in P concentration between the roots and soil solution (Schachtman *et al*. 1998; Bieleski, 1973). Most arable land in Kenya (namely Ferralsols, Acrisols, and Cambisols) have low P reserves (FURP, 1994; Gikonyo *et al*. 2006; Sanchez *et al*. 1997; Mugo *et al*. 2021). Available P levels of as low as 3.8 mg kg^{-1} have been recorded in some areas, which confirmed that the soils are deficient in P owing to the high P fixation capacities in most of the soils in Kenya (Okalebo *et al*. 2002).

Monocropping with maize, continuous use of acidic fertilizers, especially DAP, crop harvesting, and removal of crop residues probably contribute to low total N and available P. Findings by Okalebo *et al*. (2006) and Mugo *et al*. (2021) found that it is scarce for most small-scale farmers to apply the recommended P and N fertilizer rates to replenish the nutrients removed through crop harvests. The low exchangeable cations, high exchangeable acidity, low available P, and total N are characteristic features of highly weathered soils that have lost most of the base cations through leaching by heavy rainfall (Nyawade *et al*. 2019). As a result, P becomes firmly fixed by Fe and Al oxide, so available P is low (Kanyanjua *et al*. 2002; Landon, 1991; Sanchez *et al*. 1997). Therefore, low base cations, available P, N, and high Al are some of the major causes of low maize grain yield on Kenyan acid soils. Aluminum toxicity in such soils needs to be decreased by applying amendments or liming materials.

Low available P and aluminum (Al) toxicity are key factors restraining the growth of plants on acidic soils globally (Kochian *et al.* 2005; Piñeros *et al.* 2004). Acid soils cover > 12% of areas where maize is grown in Kenya (Gikonyo *et al*. 2006; Kanyanjua *et al*. 2002). These areas, especially those in medium-altitude regions, experience low maize yields with averages ranging from 1.0 to 2 t ha^{-1} against the expected average above 5.0 t ha^{-1} in the same areas (Kang'ethe, 2004; Kisinyo *et al*. 2009). According to these authors, most crops are sensitive to high Al saturation (> 20%), which affects root development and growth of many crops, thus making them inefficiently utilize the native P in the soil or added phosphate fertilizer (Kochian, 2005; Swift *et al*. 1994). Furthermore, these farmers incur grain yield losses of up to 17% due to Al toxicity (Ligeyo *et al*. 2008).

In addition, the authors noted that phosphorus use efficiency (PUE) for cereals is too low, fluctuating between 15 and 30% when compared to perennial plants of short-cycle development like maize, which requires not only large amounts of P but also faster replenishment (Lino *et al*. 2018).

Sustaining sufficient P concentration in the leaf of cereal crops such as maize is essential for photosynthesis, which is recycled later and translocated to the developing grains during the reproductive growth stage (Sklensky and Davies, 1993; Yaseen and Malhi, 2009; Meng *et al*. 2013; Nasar *et al*. 2021). Such sentiments were echoed by the findings reported by Marschner (1995) that P is taken up mainly during the active growth stage, which after that gets re-translocated into storage organs such as seeds during reproductive stages. In addition, Marschner (1995) observed that the amount of P supplied during such reproductive stages controls the subdivision of photosynthates between the source leaves and the reproductive organs such as grains, thus resulting in vigorous growth.

Treating soils with amendments such as Minjingu Rock Phosphate (MPR) results in higher P uptake due to an increase in the availability of P in the soil (Nekesa *et al*. 2011; Cheptoek *et al*. 2021). According to Kochian (2005) and Swift *et al*. (1994), there is low P uptake in unamended soils due to the crop's sensitivity to high Al saturation (> 20%), which affects root development and growth of many crops, thus making them inefficient in the utilization of the inherent P in the soil or added phosphate fertilizer (Schachtman *et al*. 1998; Faridvand *et al*. 2021; Soratto *et al*. 2022). With higher P uptake, higher yields are inevitable, especially in MPR-treated soils resulting in higher economic returns (Cheptoek *et al*. 2021). Consequently, the higher yield and income translates to higher P efficacy, demonstrating the feasibility of using MRP to increase maize productivity and economic returns.

Due to the low content of available soil phosphorus, maize production is not likely to increase without the addition of mineral or organic P (Vance *et al*. 2003; Veneklaas *et al*. 2012). As a result, the availability of P has been associated with the application of P and an increase in available P from organic amendments or mineral fertilizers, thus resulting in higher P uptake (Kwabiah *et al*. 2003; Dobermann *et al*. 2002). Nekesa *et al*. (2011) retaliated that MRP provides a liming effect on acidic soils due to its relatively high carbonate content despite its low solubility. The rise in pH and reduction of exchangeable soil acidity can also be associated with the presence of basic cations (Ca^{2+} and Mg^{2+}) (Fageria *et al*. 2009) and anions (CO_3^{2-}) in these liming materials that can react with H^+ ions from exchange sites to form H_2O and CO_2. Cations occupy the space left behind by H^+ on the exchange sites leading to a rise in pH. Such conditions allow for the dissolution reaction to occur sufficiently to provide plants with P at a rate that matches their demand (Khasawneh and Doll, 1978; Bolland *et al*. 1995). P is translocated into the reproductive areas of the plant, where high-energy requirements are needed for the formation of seeds, and hence P deficiency during later stages of growth can affect both seed development and normal crop maturity (Cheptoek *et al*. 2021).

As noted by zhou *et al*. (2021), optimal P supply corresponds well with a light interception, which enables the plant to utilize assimilates and meets their grain yield potential. Increased light interception not only results in increased photosynthetic capacity but also boosts carbon (C) translocation to the roots (Cheng *et al*. 2014; Wang *et al*. 2011; Raza *et al*. 2021; Zhou *et al*. 2021; Rahimi *et al*. 2022; Nasar *et al*. 2021). In such cases, the partitioned C serves not only as a source of energy but also as a nutritional signal in driving heightened nutrient uptake, hence productivity. Such argument is reinforced by previous observations made by Seleiman *et al*. (2021) and Raza *et al*. (2021) that plants with more leaves tend to have better growth and subsequent higher yield.

Phosphorus use efficiency (PUE) refers to produce (yield or biomass) generated per every unit of P that is taken up by the crop (Hernandez-Ramirez *et al*. 2011). Improving PUE is essential in reducing P fertilizer costs hence ensuring high yield and economic benefits at harvest (Veneklaas *et al*. 2012; Sarwar *et al*. 2016) besides minimizing environmental-related impacts caused by carrying away of P via run-off (Childers *et al*. 2011; Tiessen, 2008). PUE knowledge might be significant in evaluating physiological processes like P uptake, translocation, and accumulation in plants that will influence the final grain yield and PUE of the crop (Yaseen and Malhi, 2009).

CONCLUSION

This review has shown that soil Al toxicity and poor nutrient management, particularly for N and P, due to the high cost of fertilizers, are the key factors that have led to low maize productivity in Kenya. Inadequate and inappropriate use of fertilizers has resulted in low N and P uptake and their use efficiencies that have caused a decrease in grain yield and nutritional quality of maize. Therefore, there is a need for farmers to use nitrate N from fertilizer at the rate of 50 kg N ha^{-1} as well as replenish and amend soils through the application of MRP that is cheap and sustainable. This will enhance N and P availability, uptake, and use efficiencies and, as a result, optimize growth, grain yield, and nutritional benefits in terms of protein content and economic returns of maize.

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