DEVELOPMENTS IN INCREASING NUTRIENT USE EFFICIENCY OF APPLIED NITROGEN AND PHOSPHORUS: A REVIEW

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Abstract: Fertility decline through nutrient mining as a result of continuous cultivation and nutrients depletions lower soil productivity and pose threats to environmental health. With a geometric increase in global population, increased agricultural production must be a priority if enough food must be produced to feed the increasing human population. However, the high cost of fertilizers coupled with the low fertility status of most tropical soils suggests an increased emphasis on high efficiency of inputs for sustainable crop production. In order to minimize the threat of environmental pollution and reduce the cost of production, nutrient input to agricultural lands must remain relatively low while increasing productivity to meet projected demand. Thus, productivity and Nutrient Use Efficiency (NUE) must increase. As a result, efforts have been made by the fertilizer industry and researchers to promote approaches that would improve crop productivity while minimizing nutrient loss to the environment. Nutrient use efficiency is determined by fertilizer management as well as soil and plant-water relationships. Uptake efficiency and utilization efficiency are major approaches to sustainable nutrient use efficiency. Therefore, the application of fertilizer in the best management practices (BMPs) targeting both high yields and nutrient efficiency are good strategies that will benefit farmers and ensure environmental health. Nitrogen and phosphorus are the most limiting nutrient elements in most agricultural production systems and in many cases are the principal sources of environmental pollution. The use of appropriate N and P fertilizers, as well as balanced fertilization, are prerequisites to enhance N and P use efficiency and effectiveness as well as increasing crop biomass, soil carbon (soil organic matter) and soil health in general.

Keywords: Nutrients use efficiency, developments, nitrogen, phosphorus, balance fertilization

Introduction

Global agriculture faces multi-dimensional challenges due to increased population and threat of climate change. It is envisaged that the world population will reach 9.8 billion by the year 2050 (FAO, 2017). This population increase, will result in increased demand for food (Bordirsky *et al.*, 2015), which is expected to be achieved through the limited available land that is under serious thread as a result of urbanization, other environmental concerns and increasing water scarcity (Cakmak, 2002). Also, increasing population is declining production due to land degradation. Land degradation is currently one of the major challenges of sustainable agricultural production particularly the marginal lands (Lal, 2008; Gomiero, 2013). Prominent among the degradation indices is fertility decline as a result of continuous cultivation without replenishment especially in small farm holdings (Lal, 2008). In developed economies with high subsidies of agricultural inputs, excessive use of agrochemicals may constitute a threat to the environment with a consequence of environmental pollution and lower agricultural productivity. Addressing this by sustainable management is not only imperative in agricultural intensification but necessary if the environment is to be safeguarded. There is however diverse opinion as to the best agricultural practice that can sustain higher production as well as safeguard the environment (Borlaug, 2000; Srianivasean, 2006; Swaminathan, 2007; Perfecto and Vandermeer, 2010). One such nutrient management is nutrient use efficiency and especially the major limiting elements; nitrogen and phosphorus (Wezel *et al.*, 2014). Importantly also is the fact that global nitrogen and phosphorus fertilization are expected to rise by 2050 by 2.7 and 2.4 times, respectively (Tilman, 2000), at the same time exhibiting diminishing yields (Tilman *et al.* 2002).

Nutrient use efficiency (NUE) is the yield per unit fertilizer input (Hawkesford, 2012). There are eighteen (18) different forms of nutrient use efficiency, however, four of them are very commonly used, but are often misinterpreted (IPNI, 2007). These are; partial factor productivity (crop yield per unit of nutrient applied) which answers the question: “How productive is this cropping system in comparison to its nutrient input?”; agronomic efficiency (yield increase per unit of nutrient applied) which answers a more direct question: "How much productivity improvement was gained by the use of a particular nutrient?” , partial nutrient budget (nutrient in harvested crop per unit of nutrient applied) which answers the question: “How much nutrient is taken out of the system in relation to the amount put in?” and recovery efficiency (increase in above-ground crop uptake per unit of nutrient applied) that answers the question: “How much of the nutrient applied did the plant take up?”

Nutrient use efficiency can greatly be influenced by fertilizer management as well as soil and plant-water relationships (Johnson *et al*., 2003; Roy, 2006; Gouley, 2013). Belgiar *et al.* (2001) reported that there are three (3) main nutrient efficiencies in plant system; uptake efficiency, incorporation efficiency, and utilization efficiency. However, Baligar *et al*. (2001) and Martin (2015) indicated that uptake efficiency and utilization efficiency are most important and must be marched with yield improvement and quality. Multiple complex processes contribute to the overall nutrient use efficiency; a genetic trait of crop plants, balanced nutrient supply and excellent management practices (Marschener, 1986).

There must be increased agricultural production if enough food must be produced to feed the ever-growing human population (Fischer *et al*., 2014). However, the high cost of fertilizers coupled with the low fertility status of most tropical soils suggests an increased emphasis on high-efficiency inputs if crop production must be a profitable business. This implies that more nutrient inputs would be needed to sustain sufficient quantity and quality of food. However, an alarm has been raised by environmentalists of possible nutrients pollution to the environment as a result of fertilizer practices (Lal, 2004). In order to minimize the threat of environmental pollution and reduced the cost of crop production for the farmer, the cost of production must remain relatively low while increasing productivity to meet projected demand. This, therefore, implies that productivity and NUE must increase. These issues have stirred up efforts by the fertilizer industry and researchers to promote approaches that would improve crop productivity while minimizing nutrients losses to the environment. These approaches include; good agronomic practices otherwise known as Best Management Practices

(BMP's), improved fertilizer products (Enhanced Efficiency Fertilizers (EEF's), incorporating farmer experimentation (through participatory learning and action research) (IPNI, 2007, 2009).

Nitrogen use efficiency varies in relation to inherent plant factors, external environmental factors and management (Chikowo *et al*., 2009; Fujita *et al*., 2013). Applied nitrogen fertilizers retrieval from soils by crops rarely exceeds 20 – 30% for farmers managed fields under rainfed conditions and 30 – 55% under irrigated agriculture (Roberts, 2008; Liu *et al.*, 2016). The case of applied phosphorus fertilizers in terms of retrieval and recovery is even worst compared to nitrogen fertilizers; 10 – 30% recovery in the first year of application and one of the least mobile elements in soil (Gosh *et al.*, 2015).

Improving the nutrient use efficiency of applied nitrogen

Nitrogen is the most abundant gas in the atmosphere; however, it is inert and cannot be utilized by plants except after fixation by the nitrogen-fixing processes. Additionally, nitrogen is highly susceptible to different losses; erosion, leaching, and volatilization, especially under unfavorable conditions. Recent advances in fertilizer technology indicate best management practices (BMP) is a very viable tool in reducing the cost and supporting sustainability of both production and environment.

Best management practices imply the effective application of fertilizers to increase the efficiency of inputs used in crop productions (IPNI, 2007). The goal is to apply the most appropriate type at the right rate, time, and place. The efficiency of applied N to soils is usually low (van Duivenbooden, 1996; Erisman, 2018). The low nitrogen efficiency may be as a result of the application of inappropriate fertilizer products and/or inappropriate application time and methods (Basak, 2002). Nitrogenous fertilizer use efficiency (NUE) is generally influenced by three major factors such as; N supply from the soil, fertilizer, and other inputs, crop N uptake, and N losses from the soil-plant system (Ladha *et al*., 2005). In order to have a justifiable agricultural production, the best possible use of mineral nutrients (fertilizers) by crops is essential (IPNI, 2009). Applied N can be immobilized in soil organic matter or may be lost to the environment with the high potential to become a pollutant of ground or surface waters or to contribute to the greenhouse effect (Warren, 2008; Duke and Williams, 2008).

Agronomic practices are an important part of nutrient use efficiency (Baligar *et al*., 2001). With good management practices, which include selecting a right rate of application compatible with plant needs, placing the fertilizer at the right place where plants can easily reach the nutrients, and choosing the right application time and rate otherwise known as the 4R's of nutrient use efficiency (IPNI, 2009). In the case of N, the 4R's implies splitting the application into two or more time intervals while a basal application is recommended for phosphorus fertilizer (IPNI, 2009). Good agronomic practice also takes into account genetics and management practices that ensure maximum economic yields through the utilization of improved germplasm (Rengel, 2002; Mendes *et al.*, 2015; Ali *et al*., 2018), such as the choice of varietal type (hybrid, OPV, local) that adapt to site characteristics (soil, climate, water availability) and constraints (e.g. drought, problem soils), farmer's crop management practices (cropping system, residue management, fertilizer inputs, etc.) as well as the use of balanced fertilization (K, Mg, S, Zn, etc.) are prerequisites to enhance N and P use efficiency and effectiveness (Cianzio, 2002; Hawkesford, 2012).

One of the BMPs advocated is improved fertilizer products (Enhanced Efficiency Fertilizers EEF's). The Association of American Plant Food Control Officials (AAPFCO) has adopted the term 'enhanced efficiency fertilizers' (EEF) to characterize products that can minimize the potential of nutrient loss to the environment, as compared to reference soluble sources (Hall, 2005; AAPFCO, 1995). Enhanced efficiency fertilizers include ''slow-release'' or ''controlled-release'' fertilizers, which comprise coated, water-insoluble or slowly water-soluble products, and ''stabilized'' fertilizers which are those amended with additives that reduce the transformation rate of the products, resulting in prolong availability in the soil. Others types of EEF's include; Urea super granules for deep placement, the use of nitrification inhibitors, Reducing ammonia volatilization by urease inhibitors, Reducing ammonia volatilization and nitrate leaching/denitrification by combining urease and nitrification inhibitors, Use of ammonium sulfate to enhance N efficiency of urea (Roberts, 2008).

Trenkel (1997) classified two important groups of fertilizers as slow or controlled-release fertilizers. The slow release group is formed by condensation products of urea and urea aldehydes, of which the most significant types on the market are urea formaldehyde (UF), isobutylidene diurea (IBDU), and crotonylidene diurea (CDU) (Basak, 2002). The controlled-release group is comprised of coated or encapsulated fertilizers, such as S-coated urea (SCU) or polymer-coated urea (PCU). Roberts (2008); (Jiao *et al.*, 2018) reported that stabilized nitrogen fertilizers are those treated with inhibitors, such as nitrification or urease inhibitors, that may reduce/slow the transformation of nitrogen into forms that can easily be lost.

Controlled-release coated urea products

The terms slow-release and controlled-release are used interchangeably (Chien *et al*., 2009). However, it has become acceptable recently to apply the term controlled-release to coated or encapsulated fertilizers for which the factors determining the rate, pattern, and duration of release are known and regulated during fabrication, and slow-release be used for microbial decomposed N products such as urea formaldehyde (Shaviv, 2005; Trenkel, 1997). There has been increasing production of sulfur coated urea (SCU) products using a thin coating containing a higher N content (42–44%) (Chien *et al*., 2009). Some of these products have a double coating of urea with polymer-sealed S coating to reduce coating weight and maintain a higher N content (Trenkel, 1997). Similarly, thin PCU products are available in in some markets as controlled release N sources (e.g., ''POLYON'' coated urea by Pursell, ''ESN'' by Agrium, ''Osmocote'' by Scotts, Meister by Chisso-Asahi, and many others) (Trenkel, 1997; Ribeiro *et al*., 2016). The coatings are made of resins/thermoplastic materials with low weights of about <1% of the granule mass without affecting the N content. Contrary to the way SCU works by releasing urea through small pinholes that can result in a more difficult controlled-N release pattern, PCU releases nitrogen by diffusion of urea through the swelling polymer membrane (Trenkel, 1997). The release pattern is related to the coating composition and usually depends on soil moisture and temperature although some products are reported to be affected little by soil moisture content, pH, soil microbial activity, and even by temperature (Shaviv, 2005). It is possible, by changing or combining coatings, to formulate fertilizers which release 80% of their nutrients in pre-established time intervals such as 80, 120, 180, or even 400 days (Shaviv, 2005; Shoji *et al*., 2001; Wen *et al*., 2001; Trenkel, 1997). A one-time application of PCU may have distinct advantages over prilled urea, not just in terms of labor-saving, but also because PCU may provide a more stable and sustained N release in rainfed crop systems where well-timed split N applications may not be feasible due to variability in rainfall and soil moisture (Singh *et al*., 1995; Ribeiro *et al*., 2016). Coated urea also performed better than regular fertilizers by promoting increased grain yield and N uptake in rice in Spain (Carreres *et al*., 2003).

Despite the potential to increase N use efficiency due to the gradual supply of N of the slow- or controlled-release fertilizers, the use of such products in commercial agriculture is limited by their cost compared to conventional fertilizers (Chien *et al*., 2009). Sulfur coated urea is perhaps, the least expensive, but still costs twice as much as regular urea. The price of other slow- or controlled-release fertilizers varies from 2.4 to 10 times that of conventional soluble N sources, per unit of N (Shaviv, 2005; Trenkel, 1997). However, the effort by the fertilizer industry to search for less expensive EEF products and world concerns about the environment may help to promote the use of less soluble N fertilizers.

Urea supergranules (USG) for deep placement

These are compacted urea with about 1–3 g granules. This group of special fertilizer products has been given special attention, particularly in tropical and subtropical regions for irrigated rice (Gaudin *et al.*, 2015). The crystalline fertilizers are produced in compacted form, to reduce the surface area, hence reducing their solubility leading to a slow release of nutrients into the soil solution. Whereas in Western Europe such as super granules, briquettes, tablets or sticks are preferably used for fertilizing trees and shrubs, as well as some vegetables, such as tomatoes, pot plants etc. This is an effective N source as one or more USG are deep placed (7–10 cm depth) by hand at the center of every four rice seedling hills in rice soils during or after rice transplanting. Savant and Stangel (1998); Akter and Huda (2015) reported a significant reduction in N losses and this resulted in a significant increase in rice grain yield under flooded conditions compared to split application of prilled urea (PU). When USG are deep placed, there is a great reduction in NH_3 volatilization and this significantly reduces denitrification of nitrogen compared to surface application of Prilled Urea. Also, deep placement of USG greatly reduces nitrogen concentration of flooded water (Savant and Stangel, 1990; Gaudin *et al*., 2015). Urea super granule makes it easier for farmers to apply by hand. It has the advantage of only one-time application after rice transplanting, whereas two to three split applications are required for surface application of PU which can result in significant nitrogen loss through NH_3 volatilization. One disadvantage of applying USG is that it is a labor-intensive practice and some rice farmers in developing nations are not willing to adopt. However, super granules of NPK compound fertilizers containing urea are commercially available for tree crops and fruits in particular.

Use of stabilized fertilizers

Stabilized fertilizers are meant to reduce nitrate leaching and de-nitrification by nitrification inhibitors (Chien *et al*., 2009). Although there are many compounds known as nitrification inhibitors, Trenkel (1997) reported three products to be available on a commercial basis. These are 2-chloro-6-(trichloromethyl) pyridine (Nitrapyrin) with the trade name ‘‘N Serve,"; dicyandiamide (DCD, H_4C2N_4), which is available with several commercial names, and 3, 4-dimethylpyrazole phosphate (DMPP) with the trade name ‘‘ENTEC.’’ Another potent nitrification inhibitor, acetylene gas, was reported by Hynes and Knowles (1982). Acetylene gas is produced from urea fertilized soil by the reaction of wax-coated calcium carbide (CaC_2) with water. Freney (1997); Sempeho *et al*. (2014) reported a significant reduction in nitrification which resulted in increased yield of irrigated wheat, maize, and cotton, and flooded rice. The aim of using nitrification inhibitors is, therefore, to control leaching of nitrate by keeping nitrogen in the ammonia form for a longer time thereby, preventing denitrification of nitrate-N and increasing the efficiency of applied nitrogen.

Reducing ammonia volatilization by urease inhibitors

Urea-based N products are N fertilizers used worldwide for crop production, especially urea due to its high N content (46% N). However, NH_3 volatilization can be a significant N loss mechanism for urea when applied to the soil surface, at the early stage of plant growth (Cantarella *et al*., 2018). Hydrolysis of urea $[(NH_2)_2CO]$ to NH_4HCO_3 produces high pH that induces NH_3 volatilization under conditions of high wind, moistened soil surface, low plant canopy, high temperature among others (Chien *et al*., 2009). Kiss and Simihaian (2002) reported that the use of urease inhibitors is effective at reducing NH_3 volatilization from urea hydrolysis. They considered it an effective approach to increasing nitrogen efficiency of urea-based N products. Not fewer than 14, 000 compounds with a wide range of characteristics have been tested and are patented as urease inhibitors. Many metals have the ability to inhibit urease activity, they include: Ag, Hg, Cd, Cu, Mn, Ni, and Zn (Reddy and Sharma, 2000). Boric acid was also discovered to have an inhibitory effect on urease (Benini *et al*., 2004). Metals react with sulfhydryl groups of the urease enzyme rendering it inactive (Tyler, 1974), whereas boric acid appears to show competitive inhibition with urea (Benini *et al*., 2004). However, the effectiveness of these inorganic products is low (Reddy and Sharma, 2000; Bayrakly, 1990) and some of them are heavy metals which have restrictions for soil application. Furthermore, in some studies, the rates of application were too high to justify their use in commercial fertilizers (Bayrakly, 1990; Purakayastha and Katyal, 1998). Alternatively, micronutrients when combined with urea at the right proportion may have some appeal if they could show urease inhibition in addition to that of more effective organic inhibitors. Ammonium thiosulfate, which is an S and N fertilizer, also presents a capacity to inhibit nitrification and urea hydrolyze, but its effectiveness is low and the compound is required at high rates (Goos and Fairlie, 1988).

Phenyl phosphorodiamidate (PPDA) is a potent urease inhibitor that received extensive investigation in the early days by East German researchers in 1976. The application of PPDA significantly increased rice grain yields in only two out of eight flooded-field rice trials. They linked it to rapid degradation of PPDA due to high pH or temperature of flooded water. Broadbent *et al*. (1985) reported that adding PPDA to a urea solution applied to corn did not affect the rate of urea hydrolysis, N uptake of corn or corn yield. Recently, attention has been directed towards N-(n-butyl) thiophosphoric triamide (NBTPT), trade named ‘‘Agrotain.’’ Cantarella *et al*. (2018) reported a reduction of NH_3 loss by around 53% when NBPT-treated urea was applied to the soil compared to urea alone. Similarly, in a greenhouse study, Byrnes and Freney (1995) reported that NBTPT was more effective than PPDA at retarding urea hydrolysis and reducing the ammonium–N concentration in flooded. Urease inhibitors prevent or depressed over a certain period of time the transformation of amide-N in urea to ammonium hydroxide and ammonium, by slowing urea hydrolysis in soil. Thereby, reducing volatilization losses of ammonia. Urease inhibitors thus inhibit for a certain period of time the enzymatic hydrolysis of urea, which depends on the enzyme urease (Chien *et al*., 2009).

Similarly, ammonia volatilization and nitrate leaching/de-nitrification have been proved to reduce by combining urease and nitrification inhibitors. Ammonia volatilization and nitrate leaching/de-nitrification are mainly responsible for potential N losses from the application of urea-based products. Efforts have been made to combine urease inhibitors and nitrification inhibitors in order to increase yield and reduce the amount of N loss. Zaman *et al*. (2005) compared the treatment of combined NBTPT (urease inhibitor) and DCD (nitrification inhibitor) against NBTPT or no inhibitor in terms of N loss in a soil (pH 5.7) fertilized with urea. They reported that application of NBTPT reduced more NH_3 volatilization compared to treatments without inhibitor. However, DCD resulted in less NO_3–N leaching and denitrification loss from the soil fertilized with urea. They added that, the overall low losses of NO_3–N leaching for the treatments were due to inadequate drainage (30 mm) to remove the bulk of the nitrate from the soil surface during the period of the trial. Combining NBTPT and DCD improves their efficiency in reducing NH_3 volatilization comparing to NBTPT alone.

Improving the efficiency of applied N through the Use of ammonium sulfate

Ammonium sulfate [$(NH_4)_2SO_4$ or AS] is a weak acidic salt that is not prone to NH_3 volatilization in acidic and neutral soils (Chien *et al*., 2009). It is also a common source of N fertilizer, and therefore several studies have been conducted to investigate whether the use of AS could enhance the agronomic N efficiency of urea by reducing NH_3 volatilization. Fleisher and Hagin (1981) opined that pretreatment of soil with an NH_4 salt could increase the population of nitrifiers that could reduce NH_3 volatilization from subsequently applied urea. They reported that pretreatment with ammonium sulfate reduced NH_3 loss by half from following urea application in a neutral soil. In a field study in India, Chatterjee (2018); Kumar and Aggarwal (1988) also found that when soils of alkaline pH are treated with AS 2–4 weeks before urea application, NH_3 losses are reduced by half and this was translated into yield increase of pearl millet. Similarly, Goos and Cruz (1999) observed a similar effect of AS pretreatment 2 weeks before urea on reducing NH_3 volatilization from the subsequent urea application to soils varying widely in soil properties. The concept of this approach could be utilized in crop systems that receive more than one urea top dressing if AS is used before the first application (Goos and Cruz, 1999). An important way of improving the N efficiency of urea is partial substitute of AS for urea in the mixture. Studies revealed that mixing AS with urea reduced NH_3 volatilization losses (Vitti *et al*., 2002). This may not be unconnected to the fact that, AS rarely contribute to NH_3 losses under neutral to acidic soil conditions; besides, the dilution effect of AS–N should be taken into account since NH_3 volatilization is greater with high rate urea of application (Cantarella *et al*., 2003). Vitti *et al*. (2002) attributed the reduction in NH_3 volatilization from urea to the acidic nature of AS.

Improving the efficiency of conventional phosphorus fertilizers

There has been some interest in research and development on modifying the physical characteristics of conventional water-soluble phosphorus (WSP) fertilizers to reduce P fixation by soil, and thereby increasing P efficiency for plant uptake (Chien *et al*., 2009). Recent findings indicate the use of coated water-soluble phosphorus and urea super granules containing phosphorus and potassium nutrients to improve P use efficiency (Van de Wiel *et al*., 2015).

Coated water-soluble phosphorus (WSP) fertilizers

Recently, some fertilizer companies have developed a thin coating of WSP fertilizers (DAP, MAP, TSP) with water-insoluble polymers, with or without S (e.g., trade name ‘‘DAP-Star'' by Hi Fert), like a slow-release P fertilizer. Other brands are coated with water-soluble polymers with the trade name ‘‘Avail” by SFP to reduce the rate of P fixation by soils. Similarly, Gordon and Tindall (2006) ascertain that Avail is a polymer with a very high surface charge density of close to 1800 cm ol kg^{-1} of cation exchange capacity and it can prevent P precipitation by acting as a base for sequestration cations that responsible for of P-fixation. Similarly, studies showed that MAP coated with this polymer performed significantly better than uncoated MAP when MAP was broadcast, but it did not when banded since soil fixation of WSP is higher when broadcasted than when banded (*Chikowo et* al., 2009).

Urea super granules containing phosphorus and potassium nutrients

Savant and Chien (1990) reported that available P from DAP in USG by deep placement was as effective as broadcast and incorporation of DAP or TSP for flooded rice. Savant *et al.* (1997) reported that although initial P accumulation in rice seedlings from deep-placed USG-mixed with DAP was lower than that of incorporated TSP, P uptake from both P sources was the same 40 days after rice transplanting. Similarly, they opined that, no P activity was detected in the flood water when USG-containing DAP was deep placed. This observation clearly suggests that runoff losses of P in solution and/or P adsorbed on clays suspended in the flowing floodwater would be reduced substantially, as such, reducing eutrophication caused by P runoff from paddy fields. Several studies reported that USG–DAP management can make the fertilizer agronomically more efficient, economically more attractive with less risk, and reduce the loss of nutrients compared to the conventional use of PU and WSP fertilizers (Savant and Stangel, 1998). (Kapoor *et al*., 2008) demonstrated that deep placement of USG-containing DAP and KCl performed better than the broadcast application of urea (three splits), DAP, and KCl for rainfed rice in Vertisols. Significantly higher grain yields and straw yields, total N, P, and K uptake, and N and P use efficiencies were observed with deep placement of N–P–K compared to broadcast of N–P–K. Furthermore, the amounts of N, P, and K in the floodwater in the deep-placement treatments were negligible—similar to floodwater N, P, and K contents without fertilizer application. This implies that urea-based N–P–K compound fertilizers may be agronomically and economically feasible in super granule form by deep placement for flooded rice production.

Use of nonconventional phosphorus fertilizers

Recent advances in fertilizer technology indicate that the efficiency of non-conventional fertilizer could be improved to reduce waste, improve productivity and sustain the environment (Chien *et al*., 2009). One of such is the direct application of phosphate rock. This is an effective agronomic/economically viable alternative to the use of more expensive WSP fertilizers for crop production on soils with high P fixing capacity, especially acidic soils of tropical and subtropical savanna regions. This is because these soils have significant P fixing capacity, therefore the direct application of the less expensive phosphate rock to saturate the soils and quench the thirst of the phosphorus fixing cations will be a more efficient and economical alternative for the water-soluble phosphates (Rose *et al*., 2013). The agronomic use of PR has been extensively studied several PR sources have been commercialized for export from many African, Asian and South American countries for pastures and tree crops. The major factors affecting the agronomic effectiveness of PR are chemical and physical properties of PR that affect the solubility of PR, soil properties, management practices, climate, and crop species. Similarly, the use of reactive PR cannot only sustain crop productivity but also may minimize the eutrophication problem compared to the use of WSP sources, due to gradual release of P from PR for algal growth (Hart *et al*., 2004; Shigaki *et al*., 2006, 2007). A mixture of phosphate rock and water-soluble P has also proved feasible where agronomic use of PR may not be as feasible as WSP under conditions where the soils have low PR reactivity, high soil pH, or Crops with short maturity periods (Chien and Menon, 1995).

Use of granular nitrogen and phosphorus fertilizers containing sulfur

Soil sulphur (S) deficiency has become a major problem for crop production in many countries due to the extensive and popular use of high-analysis NP fertilizers, for example, urea, MAP, DAP, and TSP containing little/no S nutrient. Elemental S (ES) is almost 100% S, as such incorporation of ES will not significantly decrease N and P contents of these NP fertilizers compared to the incorporation of SO_4–S, such as $(NH_4)_2SO_4$ or $CaSO_4$. Thus, incorporating ES to NP fertilizers is now a common practice by some fertilizer companies. Similarly, urea fertilizer containing ES are now commercially available. This is produced by injecting molten ES into liquid urea and prilling the melt; it contains about 36% N and 20% S. Boswell and Friesen (1993) provided a comprehensive review on the use of ES fertilizers, including effects of incorporation of ES into NP fertilizers on crops and pastures. The present chapter, therefore, will discuss only the most recent developments in new NP fertilizers containing ES. It is known that ES is not plant available unless it is oxidized to SO_4–S by soil microbes, and the rate of S oxidation greatly depends on the particle size of ES (Boswell and Friesen, 1993). For this reason, some fertilizer companies have been developing processes to micronize the particle size of ES being incorporated into granular NP fertilizers. The new idea assumes that once the fertilizer granules dissolve and ES disperses back to the original fine particle size, it may rapidly enhance the rate of S oxidation in soils. The rate of S oxidation will still be slowed due to limited contact between ‘‘clustered" ES particles and soil microbes unless the ES particles are thoroughly mixed with the soil.

Incorporating farmer experimentation

Participatory learning and action research have also recently been used to improve nutrient use efficiency of crops by smallholder farmers. Another way ensuring that research findings get to the end users is through participatory learning and action research (Leitgeb *et al.*, 2011). Before now, what rural people know is assumed to be "primitive," "unscientific," or overtaken by development, and so formal research and extension must "transform" what they know so as to "develop" them. However, recently, alternative views have been unraveled which view local knowledge as a valuable and underused resource, which can be studied, collected, and incorporated into developmental activities. Neither of these views is entirely satisfactory because of the static view of knowledge implied (Scoones and Thompson, 1994). It is more important to recognize that local people are always involved in active learning, in (re) inventing technologies, in adapting their farming systems and livelihood strategies and know their environment better than anyone (Piepho *et al*., 2011). Understanding and supporting these processes of agricultural innovation and experimentation have become an important focus in facilitating more sustainable agriculture and better N and P use efficiency. Another setback of modern agricultural science is that technologies are finalized before farmers get to see them. When new technologies are appropriate for farmer’s conditions or needs, then there is a possibility of being accepted, however, if it does not fit or farmers are unwilling to make changes, then they will reject it entirely. For this reason, efforts have been made towards involving farmers in adapting technologies to their conditions. This constitutes a radical reversal of the normal modes of research and technology of many generations because it requires interactive participation between professionals and farmers. Here, the knowledge and research capacities of farmers are joined with those of scientific institutions, and at the same time strengthening local capacities to experiment and innovate. Farmers are encouraged to participate in testing new technologies, evaluate them and choose the ones they want to adopt based on their own knowledge and value systems. Although, researchers and farmers participate in different ways under this program, the most common form of this "participatory" research is researcher designed and implemented research which is then conducted on farmers' fields or farmers may implement trials designed by researchers. This is aimed at providing choices for farmers as they make farm-specific decisions and move the whole farm towards greater sustainability and hence improving the efficiency of the applied nutrients.

Conclusion

Improving the efficiency of applied N and P is a fundamental challenge facing the fertilizer industry, and agriculture in general. Recent advances in nutrient management using BMPs as tool indicates that the use of controlled-release coated urea products such as sulfur coated urea (SCU), urea supergranules (USG and stabilized fertilizers such as 2-chloro-6 (trichloromethyl) pyridine not only enhance N-use efficiency but also safeguard the environment. Similarly, urease inhibitors and use of ammonium sulfate fertilizers, and combining urease and nitrification inhibitors could be employed to curtail volatilization and enhance maximum N use efficiency. The use of coated water-soluble phosphorus fertilizers, urea super granules containing phosphorus and potassium nutrients and the use of improved rock phosphate could enhance P use efficiency, crop productivity, and sustainability of the environment. The participatory approach to nutrient management has also proved effective in maximizing nutrient use efficiency management. However, caution must be taken to ensure that improvements in efficiency do not come at the detriment of the farmers' economic viability or the environment. Therefore, application of fertilizer BMPs i.e. the right rate, right time and right place targeting both high yields and nutrient efficiency will benefit farmers, society, and the environment alike. The use of appropriate N and P fertilizers and balanced fertilization (K, Mg, S, Zn, etc.) are prerequisites to enhance N and P use efficiency and effectiveness as well as increasing crop biomass, soil carbon (soil organic matter) and soil health in general.

Conflict of Interest

Authors declare that there is no conflict of interest reported on this work.

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