



Smart Fertilizer Strategy for Better Crop Production

A. Karthik, M. Uma Maheswari

10.18805/ag.R-1877

ABSTRACT

Food security is one of the major concerns for all developing countries of the world. Even though we had attained the highest food production with the use of new technologies, we may not be able to feed the burgeoning population adequately in coming years due to stagnant crop productivity. Natural source of nutrients like organic manures and external source of nutrients, viz. fertilizers, are considered as the two eyes in plant nutrient management. Nutrient use efficiency of fertilizer is very low due to numerous pathways of losses such as leaching, denitrification, microbial immobilization, fixation and runoff. It has been estimated that around 40-70% of nitrogen, 80-90% of phosphorus, 50-70% of potassium and more than 95% of micronutrient content of applied fertilizers are lost in to the environment and results in pollution (Kanjana, 2017). Smart fertilizers like slow and controlled release fertilizers, nanofertilizers and bioformulation fertilizers are the new technologies to enhance the nutrient use efficiency their by improving crop yield in sustainable manner. The use of slow and controlled release fertilizers increase nutrient use efficiency, minimize the risks like leaf burning, water contamination and eutrophication. Nano-fertilizers are the nano-particles-based fertilizers, where supply of the nutrients is made precisely for maximum plant growth, have higher use efficiency, exploiting plant unavailable nutrients in the rhizosphere and can be delivered on real time basis into the rhizosphere or by foliar spray (Priyanka Solangi *et al.*, 2015). The small size, high specific surface area and reactivity of nano fertilizers increase the solubility, diffusion and availability of nutrients to plants and enhance crop productivity. Bioformulation is microbial preparations containing specific beneficial microorganisms which are capable of fixing or solubilizing or mobilizing plant nutrients for promoting plant growth and crop yield. Smart fertilizers are the better option for the farmers to increase their crop yield with low input cost in sustainable way without degrading natural environment.

Key words: Bioformulation, Crop yield, Nanofertilizers, Nutrient use efficiency.

World agricultural cropping systems intensively using large amount of fertilizers, pesticides, herbicides to achieve more production per unit area. Continued fertilizer inputs are essential to sustain and increase food production. However, there are problems associated with mineral fertilizer use like environment pollution (soil, water, air pollution), low input use efficiency, decrease quality of food material, develop resistance in different weeds, diseases, insects, less income from the production, soil degradation, deficiency of micro nutrient in soil, toxicity to different beneficial living organism present above and below the soil surface *etc.* In present agriculture fertilizer contributes to the tune of 50% of the agricultural production but increasing use higher doses of fertilizers does not guarantee to improved crop yield but it leads several problems like degradation of soil and pollution of surface and underground water resources.

Approximately, more than 90% of Indian soil samples exhibited low nitrogen and phosphorus content, while 50% of soil samples were low in potassium. But these nutrients are highly essential for better plant growth and development and higher yield and quality. Likewise, among the micronutrients, zinc (49%) and boron (33%) are the most deficient nutrient as compared to other nutrients, viz. molybdenum (13%), iron (12%), manganese (5%) and copper (3%) (Singh 2008). These multi-nutrient deficiencies in soil along with poor soil organic matter, lower fertilizer response ratio and imbalanced fertilization cause stagnant level of crop productivity. The fertilizer response ratio in the irrigated areas of the country has decreased drastically. It

Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore-641 003, Tamil Nadu, India.

Corresponding Author: M. Uma Maheswari, Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore -641 003, Tamil Nadu, India. Email: umavalarmathi987@gmail.com

How to cite this article: Karthik, A. and Maheswari, M.U. (2021). Smart Fertilizer Strategy for Better Crop Production. *Agricultural Reviews*. 42(1): 12-21. DOI: 10.18805/ag.R-1877.

Submitted: 18-02-2019 **Accepted:** 20-10-2020 **Online:** 07-01-2021

has been reported that 27 kg NPK ha⁻¹ was required to produce one ton of grain in 1970, while the same level of production can be achieved by 109 kg NPK ha⁻¹ in 2008. The optimal NPK fertilizer ratio of 4:2:1 is ideal for crop productivity, while the current ratio is being maintained at 6.7:3.1:1 in India due to the excessive use of nitrogenous fertilizers. In order to achieve a target of 300 million tons of food grains and to feed the burgeoning population of 1.4 billion in the year 2025, the country will require 45 Mt of nutrients as against a current consumption level of 23 Mt.

The nutrient use efficiency is still very low due to numerous pathways of losses such as leaching, denitrification, microbial immobilization, fixation and runoff. It has been estimated that around 40-70% of nitrogen, 80-90% of phosphorus, 50-70% of potassium and more than 95% of micronutrient content of applied fertilizers are lost in the environment and could not reach the plant which causes not only large economic and resource losses but also very

serious environmental pollution. Therefore, to increase the nutrient use efficiency and improve the crop productivity from stagnant level and to manage biogeochemical cycles in a sustainable way (Rumpel *et al.*, 2015), alternate advanced technology is urgent need of the hour. Smart fertilizers may be a solution to enhance food production and environmental quality. In the sense of a circular economy, these smart fertilizers may be based on the innovative use of harvesting residues. This includes the development and application of modern biotechnological tools, such as Plant Growth Promoting Rhizobacteria (PGPR) and Diazotrophic N_2 fixing bacteria as alternatives to conventional fertilization.

Current Status of fertilizers in World and India

Since 2014, important reforms have been implemented in the fertilizer sector. These include the neem-coating of urea, which has likely reduced the diversion of fertilizer meant for Indian farmers; and gas-pooling, which should increase efficiency of domestic urea production. Both steps should help small farmers by improving their access to low cost fertilizer. They will also provide good building blocks for further fertilizer sector reform. The government budgeted Rs. 73,000 crore about 0.5 per cent of GDP on fertilizer subsidies in 2015-16. Nearly 70 per cent of this amount was allocated to urea, the most commonly used fertilizer, making it the largest subsidy after food. Of all the fertilizers, urea dominates the sector and it is the most produced (86 per cent), the most consumed (74 per cent share) and the most imported (52 per cent). It also faces the most government intervention. Urea is the most physically controlled fertilizer, with 50 per cent under the Fertilizer Ministry's movement control order compared with 20 per cent for DAP and MOP. It also receives the largest subsidies, in outlay terms (accounting for nearly 70 per cent of total fertilizers subsidy) and as proportion of actual cost of production (75 per cent per kg, compared with about 35 per cent for DAP and MOP). DAP and MOP producers and importers receive a Nutrient Based Subsidy (NBS) based on a formula that determines the amount of N, P and K in a given amount of fertilizer. Per kg subsidies on DAP and MOP fertilizer are hence fixed-they do not vary with market prices. Imports of DAP and

MOP are also not controlled. The prices farmers face are thus deregulated market prices adjusted by fixed nutrient subsidy. Government involvement in DAP and MOP is limited to paying producers and importers a fixed nutrient based subsidy which works out to be roughly 35 per cent of the cost of production.

The crop production is strongly dependent on N and P, which are essential and irreplaceable nutrients for plant growth and to maintain life in the world. Long-term data obtained between 1960 and 2010 for maize, rice and wheat production systems indicated that around 48% of crop N was contributed by inorganic fertilizers (Ladha *et al.*, 2016). Nevertheless N and P present a significant difference in terms of their availability. In this sense, the supply of N is currently unlimited due to the production of urea by the Haber Bosch process (Dawson and Hilton, 2011), which industrially produces around 100 Tg N yr (Ladha *et al.*, 2016). On the other hand, phosphate rock reserves are finite and there is a critical concern about the availability and cost of phosphate rock in the future. In this sense, Elser and Bennett (2011) stated: "More important than the amount of P in the ground is how much it will cost to get it out". A recent meta-analysis carried out by Valkama *et al.*, (2016) showed that yield response to P fertilization varied considerably in grassland systems and initial soil tests for P do not always predict this behavior. They described that the major sources of variation in yield responses to annually applied P were soil type specific. In many situations P fertilizer inputs, especially in tropical areas, are rapidly fixed by the soil matrix and not available for plant uptake. Therefore, the emerging global challenge of the issues associated with P supply is to improve the overall P-use efficiency of plants.

Conventional fertilization practices: Environmental consequences

The type of soils and their management have a strong influence on the conventional fertilizer use efficiency. Continuous application of N and P fertilizers in addition to the unbalanced and suboptimal fertilization (e.g., by the exclusive application of N- and P-containing fertilizers such as urea and diammoniumphosphate) for long periods of time has led to soil nutrient depletion, especially when the entire crop biomass is removed from land (Tesfay and Gebresamuel, 2016). At present most of the agricultural activities are confined to marginal land with low OM and nutrient content (Ngo *et al.*, 2014). On such soils, the application of mineral fertilizers can cause accelerated acidification and further nutrient and OM losses.

Soil acidity is one soil property contributing to P-fixation (Mora *et al.*, 2004), decreasing its availability for plant nutrition. More than 50% of P incorporated in these soils is fixed as organic P (Borie and Rubio, 2003) and may contribute to the residual fraction (Velasquez *et al.*, 2016). Thus, huge amounts of conventional P fertilizer need to be applied annually to maintain available P levels in soil-plant systems. N and P fertilizer application at levels exceeding plant requirements due to low acquisition efficiency leads

Global demand and supply of nutrients (FAO, 2018).

Nutrients	Demand (in MT)	Supply (in MT)
Nitrogen	115.4	168.9
Phosphorus	44.1	51.2
Potassium	34.9	47.2
Total	194.4	267.3

Fertilizer status in India (Annual Review, FAI, 2017).

Fertilizer	Consumption (in MMT)	Production (in MMT)	Import (in MMT)
Nitrogen	16.7	13.4	5.5
Phosphorus	6.7	4.6	4.4
Potash	2.5	-	3.7
Total	25.9		

to significant environmental consequences in many parts of the world due to N losses, such as: nitrate (NO_3) and phosphate (PO_3) leaching, NH_3 volatilization and nitrous oxide (N_2O) emission. Transport of P and N from agricultural soils to surface waters has been linked to eutrophication of freshwater and estuaries. These negative environmental consequences associated with fertilizer inputs further emphasize the need of technological approaches to improve nutrient management in modern agriculture. In addition, current agricultural activities contribute up to 20% to the annual atmospheric emissions of GHG, such as methane (CH_4) and carbon dioxide (CO_2) (Lemke *et al.*, 2007). Even higher contribution was noted for N_2O (about 60%) (Smith *et al.*, 2007), which is a potent GHG and catalyst for stratospheric ozone depletion (Yang *et al.*, 2014), with more than 300 times the global warming potential than CO_2 . Its emission is closely related to mineral fertilizer input. Agricultural wastes such as dairy slurry or manure and biomass after harvesting may also be a source of GHG emissions. Improvement of organic residue recycling in agriculture may be a solution in view of sustainable intensification of agricultural practices and could contribute to increase soil C storage, thereby improving soil quality and to some extent mitigating atmospheric GHG concentrations (Chabbi *et al.*, 2017).

Environmental effects of using synthetic fertilizers

Pollution to underground water source

- Some of the synthetic compounds used to manufacture chemical fertilizers can have negative environmental effects when allowed to run off into water sources. Nitrogen that flows into surface water by farmland accounts for 51% of human activities. Ammonia nitrogen and nitrate are main pollutant in rivers and lakes, which leads to eutrophication and ground water pollution.

Destroying soil structure

- With long-term and large-scale use of chemical fertilizer, some environment issues will appear, such as soil acidification and crust. Because of using quantities of nitrogen fertilizer, instead of organic fertilizer, some tropical farmland is in severe soil crust, leading to ultimately lost the farming value. Effects of chemical fertilizers on soil are great and irreversible.
- Long-term use of chemical fertilizer can change the soil pH, upset beneficial microbial ecosystems, increase pests and even contribute to the release of greenhouse gases.
- Many types of inorganic fertilizers are highly acidic, which in turn often increases the acidity of the soil, thereby reducing beneficial organisms and stunting plant growth. By upsetting this natural ecosystem, long-term use of synthetic fertilizer can eventually lead to a chemical imbalance in the recipient plants.
- Repeated applications may result in a toxic buildup of chemicals such as arsenic, cadmium and uranium in the soil. These toxic chemicals can eventually make their way into your fruits and vegetables.

Water eutrophication

The nitrogen-rich compounds found in fertilizer run-off is the primary cause of a serious depletion of oxygen in many parts of the ocean, especially in coastal zones; the resulting lack of dissolved oxygen is greatly reducing the ability of these areas to sustain oceanic fauna. Visually, water may become cloudy and discolored (green, yellow, brown, or red). High application rates of inorganic nitrogen fertilizers in order to maximize crop yields, combined with the high solubility's of these fertilizers leads to increased runoff into surface water as well as leaching into groundwater. The use of ammonium nitrate in inorganic fertilizers is particularly damaging, as plants absorb ammonium ions preferentially over nitrate ions, while excess nitrate ions which are not absorbed dissolve (by rain or irrigation) into runoff or groundwater.

Ideal fertilizer

- Nutrient release is to match with crop requirements.
- Maximum percentage recovery to achieve the largest return for the cost of the input.
- Minimum detrimental effects on the soil, water and atmospheric environment (Umesha *et al.*, 2017).

Environmentally friendly fertilizers

(EFFs) offer an effective way to improve nutrient efficiency, to minimize leaching and volatilization losses of fertilizers and to reduce environmental hazards. They reduce environmental pollution from nutrient losses by retarding or even controlling the release of nutrients into soil. They are also referred to as "enhanced efficiency fertilizers" (EEFs) (Chalk *et al.*, 2015; Timilsena *et al.*, 2015). Usually, EFFs are formulated in such a way that nutrients are coated with environmentally friendly materials, which can be degraded in soil and converted into carbon dioxide, water, methane, inorganic compounds or microbial biomass.

New technologies – Smart fertilizers

In order to enhance nutrient use efficiency, new types of smart fertilizers with controlled nutrient release are needed. The development of such fertilizers could be based on the use of microorganisms (biofertilizers) and/or nanomaterials (nanofertilizers).

Slow / Controlled release of fertilizer

Most commonly used commercial fertilizers are water soluble quick-release fertilizers (QRFs) that are predictably readily available for plants when properly placed in soil. Quick-release fertilizers are ideal for pre-plant applications, side dressing, hydroponics, or fertigation for many crops, including vegetables. They are highly practical if nutrient leaching or immobilization of nutrients by soil particles is not a serious concern, especially if unpredictable, high-leaching/flooding events do not occur. If conditions are favorable, less expensive QRFs have proven to be effective in crop production. In the best conditions, QRFs become available to plants at a consistent rate (Trenkel, 2010). They

will release all readily available nutrients in a short period of time after being properly applied to soil with appropriate soil moisture. In other words, their release curve is immediate and does not synchronize with or match the dynamic needs of crop growth, which is why applying timely side dressings is necessary. In fact, crop nutrient requirements change as plants develop.

According to Trenkel (1997), slow- or controlled-release fertilizers are those containing a plant nutrient in a form, which either (a) delays its availability for plant uptake and use after application, or (b) is available to the plant significantly longer than a reference “rapidly available nutrient fertilizer” such as ammonium NO_3 or urea, ammonium phosphate or potassium chloride (AAPFCO, 1995). There is no official differentiation between slow release and controlled-release fertilizers. However, the microbial decomposed N products, such as urea-formaldehydes, are commonly referred to as slow-release fertilizers and coated or encapsulated products as controlled-release fertilizers (Trenkel, 1997). Delayed availability of nutrients or consistent supply for extended time periods can be achieved through a number of mechanisms. These include semi permeable coatings for controlled solubility of the fertilizer in water, protein materials, occlusion, chemicals, slow hydrolysis of water-soluble compounds of lower molecular weights and some other unknown means (Naz and Sulaiman, 2016). Other options include utilization of semi-permeable materials and sensors of chemical or biological origin within the fertilizer. These are advanced materials, whose physical or chemical properties can change in response to an external stimulus such as temperature, pH and electric or magnetic fields. Nowadays, clay minerals are being used for encapsulating agrochemicals such as fertilizers, plant growth promoters and pesticides due to their high surface area, large adsorption power, easily modified surfaces and their colloidal nature. Clay minerals are natural and relatively cheap components of soils and being used as the reservoir and cache of nutrient elements.

Slow-release fertilizers (SRF)

The release rate of a nutrient from the fertilizer must be slower than that from a fertilizer in which the nutrient is readily available for plant uptake. Nitrogen products decomposed by microbes are commonly referred as SRF fertilizers. Some SRFs such as N-SURE are made in factories. However, some such as manure are naturally originated and cannot be formulated to permit controlled release. The nutrient release pattern of SRFs is fully dependent on soil and climatic conditions. Slow-release fertilizer releases nutrients gradually with time and it can be an inorganic or organic form. An SRF contains a plant nutrient in a form that makes it unavailable for plant uptake and use for some time after the fertilizer is applied. Such a fertilizer extends its bioavailability significantly longer than QRFs such as ammonium nitrate, urea, ammonium phosphate, or potassium chloride.

Based on the source, there are two types of SRF fertilizers: natural and artificial

Natural SRFs include plant manures, such as green manure or cover crops, all animal manures (chicken, cow and poultry) and compost (Shukla *et al.*, 2013). Because of their organic nature, these must be broken down by microbial activity before the nutrients can be released to crops. In general, organic fertilizers may take a long time to release nutrients and these nutrients may not be available when the plant needs them. The duration of nutrient release of this type of organic fertilizers mainly depends on soil microbial activity that is driven by soil moisture and temperature. Organic SRFs contain both macro-nutrients (nitrogen, phosphorus, potassium, *etc.*) and micro nutrients (iron, manganese, copper, *etc.*). The nutrient concentrations of organic SRFs are relatively lower than those of synthetic SRF fertilizers.

Synthetic SRFs

Synthetic SRFs are sparingly water-soluble. The bioavailability of this type of fertilizers (typically in pellet or spike form) depends on soil moisture and temperature. Nutrients are released throughout a period of time that may range from 20 days to 18 months (Trenkel, 2010). Therefore, fewer applications are needed with SRFs, but nutrients are released based upon the temperature and moisture conditions in the soil, which may not match the due to varying weather conditions (Trenkel, 2010). Synthetic SRFs often contain a single nutrient at a much higher level than would occur in a natural SRF. For example, N-Sure® is a SRF that contains 28 per cent nitrogen (28-0-0).

Controlled-release fertilizers (CRF)

Controlled-release fertilizers (CRF) are typically coated or encapsulated with inorganic or organic materials that control the rate, pattern and duration of plant nutrient release. Polymer-coated urea exemplifies CRFs (Loper and Shober, 2012). These fertilizers control the release of nutrients with semi-permeable coatings, occlusion, protein materials, or other chemical forms, by slow hydrolysis of water-soluble, low-molecular-weight compounds, or by other unknown means (Trenkel, 2010). Most importantly, the release rate of a CRF fertilizer is designed in a pattern synchronized to meet changing crop nutrient requirements. Eg. S-coated urea, Polymer-coated urea, Coating of WSP fertilizers with water-insoluble polymers (DAP, MAP, TSP - DAP-Star by Hi Fert.), Urea super granules containing phosphorus and potassium, Fluid versus granular water-soluble phosphorus fertilizers and Ammonium polyphosphates.

Advantages of using CRFs and SRFs

- The danger of over-fertilizing is reduced as the release of fertilizers occurs gradually.
- A balanced fertilizer mixture is provided at all times as the plants get what they need at different growth stages.

- Nutrients do not leach from the substrate so the plants receive all the nutrients applied.
- Reduce possible losses of nutrients- slower leaching and run off, evaporation losses of ammonia and enhanced nutrient-use efficiency.
- Decreases risk of environmental pollution.
- Slower release rate- plants are able to take up most of the fertilizers.
- Reduce labour capital- less frequent application is required.
- Reduction of fertilizer-associated risks such as leaf burning, water contamination and eutrophication.
- Reduced application and labor costs. Additionally, avoidance of fertilizer application in late growth stage eliminates plant damages to crops.
- Lowered soil pH in alkaline soils for better bioavailability of some nutrients. Applying sulfur-coated urea will probably increase soil acidity because both sulfur and urea contribute to increasing the acidity (lowering soil pH) of the soil. Consequently, phosphorus or iron may be more bioavailable and benefit some crops like blueberry, potato and sweet potato (Liu and Hanlon, 2012). In addition, sulfur is an essential nutrient for all crops.

Disadvantages of Using CRFs and SRFs

- Most coated or encapsulated CRFs and SRFs cost considerably more to manufacture than conventional fertilizers. This extra cost increases growers' crop production costs.
- Applying sulfur-coated urea almost always lowers soil pH as aforementioned. However, this acidification may cause nutrient disorders such as calcium deficiency or magnesium deficiency if there is not a proper nutrient management program.
- Nutrient deficiencies may occur if nutrients are not released as predicted because of low temperatures, flooded or droughty soil, or poor activity of soil microbes.
- Possible uncontrolled nutrient release of SRFs. Use efficiency of SRFs may be enhanced by planting shelter belts or nutrient trap crops where runoff is likely to occur.

Nanotechnology

The word "nano" comes from Greek that means "dwarf," and "technology" means visualise, characterise, produce and manipulate the matter of the size into 1-100 nm. Royal

Society and Royal Academy of Engineering (2004) defined that "Nanotechnology is the design, fabrication and utilization of materials, structures, devices and systems through control of matter on the nanometer length scale and exploitation of novel phenomena and properties (physical, chemical, biological) at that length scale in At Least One Dimension". Nanoparticles are having wonderful properties like smaller size, *i.e.* nanometre scale, higher surface to volume ratio and greater surface reactivity with unique quantum size effects like mechanical, electrical, optical, magnetic, thermal stability and catalytic activity (Ghormade *et al.*, 2011). Nanotechnology involves the design, synthesis and use of materials at nanoscale level, ranging from 1 to 100nm (EPA, 2007). At this scale, the physical, chemical and biological properties of materials differ fundamentally from the properties of individual atoms, molecules, or bulk matter (Mansoori, 2005). The ability to manipulate matter at the nanoscale can lead to improved understanding of biological, physical and chemical processes and to the creation of improved materials, structures, devices and systems that can be used in agroecosystems (Sastry *et al.*, 2011).

The advanced technology, *i.e.* nanotechnology, has also come to revolutionise the fertilizer industry by making the fertilizer as 'smart fertilizer' through smart delivery systems in order to improve fertilizer formulation by minimising nutrient loss and increased uptake in plant cell, for which slow or controlled release fertilizers can be developed by using clay minerals, polymers, nanocomposites (hybrid polymer and clay minerals) and metal oxides through various methods like nanoencapsulation, spray drying, core shell preparations and electrospinning techniques

Nanofertilizers

Nano-fertilizers are nutrient carriers of nano-dimensions ranging from 30 to 40 nm (10^{-9} m or one-billionth of a meter) and capable of holding bountiful of nutrient ions due to their high surface area and release it slowly and steadily that commensurate with crop demand. Subramanian *et al.*, (2008) reported that nano-fertilizers and nanocomposites can be used to control the release of nutrients from the fertilizer granules so as to improve the NUE while preventing the nutrient ions from either getting fixed or lost in the

Difference between slow and controlled release products (Source: Haifa, Israel, 2015).

	Multicote	SCU	IBDU	Methylene Urea, Ureaform
Technology	Polymer coating	Sulphur based coating	Urea reaction product	Urea reaction product
Release mechanism	Diffusion	Rapture of coating	Hydrolysis	Microbial degradation
Longevity	2-16 months	2-2.5 months	Depends on particle size	MU: 3 months UF: 12 months
Release controlling factors	Temperature	Microbial activity, moisture, temperature	Soil moisture, temperature	Microbial activity, moisture, temperature, pH, organic matter
Controlled release N (% of total N)	95%	40-50%	85%	MU: 50% UF: 20%

environment. Nano-fertilizers have high use efficiency and can be delivered in a timely manner to a rhizospheric target. There are two approaches for nanoparticle synthesis, one is top down approach such as milling, high pressure homogenization and sonication, second is bottom up approach involves reactive precipitation and solvent displacement (Sasson *et al.*, 2007). Different type of nanomaterials like metal, metal oxide, silicates and polymeric nanoparticles, quantum dots, nanobarcode, nanotube, nanoemulsions, nanofibres, nanoliposomes, nanosensor and others have been used as building blocks to create novel structures and introduce new properties in the nanoscale level for developing the agriculture and food market in the world. During the 21st century, nanotechnology will make a significant impact on World's economy, industry and people's lives.

According to Mastronardi *et al.* (2015) there are three main types of nanofertilizers: nanoscale fertilizer (synthesized nanoparticles), nanoscale additives (bulk products with nanoscale additives) and nanoscale coating or host materials (product coated with nanopolymer or loaded with nanoparticles). Slow-release nanofertilizers and nanocomposites are suitable alternatives to soluble fertilizers. Nutrients are released at a slower rate during crop growth, thereby reducing loss. Slow release of nutrients in the environments could be achieved by using zeolites (natural clays), which act as a reservoir for nutrients that are released slowly (Manjunatha *et al.*, 2016). The mineral nutrients required for plant nutrition can be encapsulated inside nano-materials such as nanotubes or nanoporous materials, coated with a thin protective polymer film, or nanoscale particles. Depending on the application, it is possible to use synthetic or natural nanoparticles obtained from various sources, including plants, soils and microorganisms. Nanoclays, which naturally occur in soils, have been considered important tools in modern agriculture due to their physicochemical properties (Sekhon, 2014). Nanoclays can be used to stabilize enzymes and thereby increase their catalytic activity for different biotechnological purposes.

Slow or controlled release nanofertilizers

Fertilizers play a pivotal role for maximising the agricultural production; particularly, water-soluble and quick-release fertilizers are being used by the farmers in general, though it contains higher amount of nutrients but it releases the nutrients very quickly and lost through various pathways. The technology is designed for the fertilizer to release their nutrient contents gradually and to coincide with the nutrient requirement of a plant (Junejo *et al.*, 2011). The quantity and duration of the plant nutrient release mainly depend upon the coating materials of controlled release fertilizer. According to Trenkel (1997), controlled release fertilizers (CRFs) must meet the following three criteria: (1) less than 15% of the CRF nutrients should be released in 24 h; (2) less than 75% should be released in 28 days and (3) at least 75% should be released by the stated release time (40-360

days). slow or controlled fertilizers can be developed by using the methods like encapsulation technique through coating, coacervation, sol-gel preparation, spray drying, core shell preparation, electrospinning, etc., in which various materials like clay minerals, polymers, porous structured metal oxides and mesoporous silica are used.

Nanosensor/nanobiosensor on plant nutrient management

A nano device or nano sensor can be simply defined as any manufactured device whose dimensions are on the scale of 1-100 nm and whose properties exploit the unique properties of nanoscale materials. Nanobiosensor is a compact analytical device/unit and called as modified version of a biosensor in which the immobilised layer of biological material like proteins, DNA/RNA, viruses, cellular lipid bilayers, microbial cells and others are in contact with the sensor that analyses the biological signal and converts into electrical signal. Nanobiosensor can be effectively used in agriculture for sensing a wide variety of fertilizers, herbicides, pesticides, pathogen, moisture, soil pH and others for enhancing the crop productivity. These biosensors may have a huge impact on the precision farming methods. Nanosensors can be linked to a GPS and distributed throughout the field for real-time monitoring of disease, crop health, soil conditions and their potential problems such as soil nutrient depletion and water deficit. Networks of wireless nanosensors positioned across cultivated fields provide essential data leading to best agronomic intelligence processes with aim to minimise resource inputs and maximising output and yield. Such information and signals include the optimal times for planting and harvesting crops and the time and level of water, fertilizers, pesticides, herbicides and other treatments that need to be administered given specific plant physiology, pathology and environmental conditions. For diagnosing the nutrient deficiency in plants, nanosensors are impregnated with nanoparticles that can be used to determine the nutrient status and deficiency of the plants, which assist in taking up appropriate and timely corrective measures to reduce the yield reduction.

Nano-nutrients may be applied by foliar mode on two week-old plants. It is better to use aerosol sprayer for spraying of nano-nutrients where the loss to the environment is only 14.5% as compared to 33% with normal sprayer. The optimum doses of application of some of the plant nutrients have already been standardized (for example P: 40 ppm, Fe: 30 ppm, Mg: 20 ppm, Zn: 10 ppm). The nanoparticles take 48-72 h time to enter into the plants through leaf hole, therefore, if there is any rain within 3 days time repeat application is needed. In general, nanoparticle size less than 20 nm is the best for penetration through foliar application.

Benefits of nanofertilizers

• Solubility and dispersion of mineral micronutrients

Oxide form of fertilizers that contains higher nutrient content can be converted into soluble form by reducing their size, shape and soluble nature. So, the bioavailability of the

micronutrient can be enhanced by increasing the solubility and reducing the fixation ability in the soil.

• Nutrient use efficiency

Nanofertilizers are help to increase the nutrient use efficiency and uptake ratio because of the smaller size of the particle that can easily penetrate into the root and leaf cuticular cells through soil and foliar applications.

• Controlled release

Nanoencapsulated slow and controlled release fertilizers supply the nutrients in precisely controlled manner over a period of time and improve the nutrient use efficiency. Surface coatings of nanomaterials on fertilizer particles hold the material more strongly due to higher surface tension than the conventional surfaces and thus help in controlled release.

• Effective nutrient release

The slow or controlled release nanostructured formulations are best for controlled release of nutrients for prolonged period of plant growth. The encapsulation technique in nano fertilizers helps in reducing the nutrient loss rate significantly (Cui *et al.*, 2011).

Bioformulation fertilizer

Microbe-based formulations also known as bioformulations are more robust than synthetic chemicals as the formulation product of a single microbe may involve direct interactions with pathogens and numerous mechanisms take part in disease suppression and plant growth promotion (Rodrigo, 2011). Burges and Jones (1998) stated bioformulation comprises aids to preserve organisms, to deliver them to their targets and once there to improve their activities, whereas Arora *et al.* (2010) define the term bioformulation to preparations of microorganism(s) that may be partial or complete substitute for chemical fertilization/pesticides. But any operative definition must include an active ingredient, a carrier material and an additive. The active ingredient is mostly a viable organism; it may be live microbe or spore and its survival during storage is very essential for successful formulation development.

Encapsulating microorganisms in carrier materials (bioformulation) is designed to protect them during storage and from adverse environmental condition (pH, temperature, *etc.*) thus ensuring a gradual and prolonged release (Kim *et al.*, 2012). Materials suitable for immobilization and preservation of bacteria include alginate gels, synthetic gels (Sol-Gel), polyacrylamide, agar and agarose, polyurethane, vermiculite and polysaccharides. In addition, composite materials based on biodegradable polymer clay or nanoclays are being studied, including nanocomposites. Encapsulation of free-living diazotrophic bacteria has been considered as one of the possible alternatives for inorganic N fertilizer for promoting plant growth and crop yield. One group of microorganisms beneficial for plant growth is PGPR, a heterogeneous group of bacteria that can be found in the rhizosphere, at root surfaces and in association with roots.

These bacteria have several functions, including production and regulation of phytohormones, release of nutrients to plants (e.g., P, N-fixation, siderophores, among others) and control of phytopathogens (production of antibiotics and siderophores) (Egamberdieva and Adesemoye, 2016).

Phosphobacteria, phytate-mineralizing bacteria and phosphate solubilizing bacteria have been commonly isolated from soil and proposed as inoculants for agricultural improvement. They may be used to develop bacterial or enzyme systems as biofertilizers to overcome the limitations of conventional fertilizers in acidic soils, as well as for developing added value products from agricultural wastes. Low N acquisition by plants is a limiting factor in agricultural ecosystems and there is interest in using N_2 fixing bacteria as an alternative to conventional fertilization. Free living N_2 fixing bacteria have been considered as an alternative to conventional N fertilizer for promoting plant growth and several research studies reported significant increases in grain and shoot biomass yield from plants inoculated with free living diazotrophic bacteria. However, it is well known that bacteria directly inoculated in the soil system could be adversely affected by competition with native micro organisms, unfavorable physicochemical conditions and fluctuating pH and temperature.

Broadly two types of bioformulations are available, liquids and solids (Burges and Jones, 1998), although in these days there are so many other types of bioformulation available and being used all over the world. Formulations for nutrient uptake In the last few years, the use of microbial inoculants is realized as an effective way of providing nutrients to plants since it would substantially reduce the use of chemical fertilizers and hence there are an increasing number of biofertilizers that are commercially produced for various crops (Trabelsi and Mhamdi, 2013).

Liquid Bio-formulations are the microbial preparations containing specific beneficial microorganisms which are capable of fixing or solubilizing or mobilizing plant nutrients by their biological activities. Humic acid in combination with *Pseudomonas fluorescens* can serve the dual purpose of production and protection for the crops. Humic acid, a derivative of lignite coal can be a suitable fertilizer for the soil while *Pseudomonas fluorescens*, which acts as a microbial pesticide. The bioformulations, which have molecular weight in the range of 5000-30000 and are classified into two categories as humic acid and fulvic acid. They are the complex mixtures of many different acids containing carboxyl and phenolate groups so that the mixture behaves functionally as a dibasic acid or occasionally, as a tribasic acid. These molecules act as bio-stimulants and chelating agents provide stimulus for the growth of plants and maturation of seedlings and make unavailable trace quantities of minerals available for plants. They act as a food source for beneficial soil microorganisms, also prevent the soil erosion and in turn enhance the water holding capability of soil. Humic acid is not a fertilizer as it does not directly provide nutrients to plants but is a compliment to

fertilizer. Humic acid stimulates microbial activity by providing the indigenous microbes with a carbon source for food, thus encouraging their growth and activity. Soil microbes are responsible for solubilizing vital nutrients such as phosphorus which is absorbed by the humic acid and in turn made available to the plant. The microbes are also responsible for the continued development of humus in the soil by breaking down or decomposing the organic matter.

Quality criteria of carriers for bioformulations

- High water holding and water retention capacity - suitable for as many bacteria as possible.
- Cost effective.
- Nearly neutral pH or easily adjustable and good pH buffering capacity.
- Available in adequate amounts and nontoxic in nature.
- Carriers used for seed coating should have a good adhesion to seeds.
- Easily biodegradable and nonpolluting.
- Supports growth and survival of bacteria and amenable to nutrient supplement.

Liquid fertilizers

Liquid fertilizers are concentrates of water-soluble synthetic chemicals or powders that contain mixes of N-P-K (Nitrogen-Phosphorus-Potassium) as well as insecticides, fungicides, weedkillers, or wetting agents.

Advantages

- Even application, identical nutrients or control technology in every drop.
- Provides a uniform application.
- Nutrients become readily available to plants
- Can be ground applied or foliar applied (taken up by roots or leaves of plants).
- Foliar applications allow for fast corrections to mid-season deficiencies.
- Ease of blending. Mixes well with other lawn care pesticides, other control or soil amendment technologies.
- Available for both starter and in-season applications.
- Phosphorus is more mobile in liquid applications.
- More control over creating your own mix.
- Easy clean-up.
- Less chance of drift to nearby flower and shrub beds.

Other smart formulations

Polymers

Polymers are widely used in agriculture especially for fertilizer development. Smart polymeric materials have been applied to smart delivery systems of a wide variety of agrochemicals. A broad range of synthetic materials, such as petroleum-based polymers, have been used to encapsulate water-soluble fertilizers. Polysulfone, polyacrylonitrile, polyvinyl chloride, polyurethane and polystyrene are the main materials currently used for coating. Tao *et al.*, (2011) studied the use of a triple polymer fertilizer to encapsulate and enhance the mechanical properties of urea. They suggested that polyethylene in a first layer, poly

(acrylic acid-co-acrylamide) as superabsorbent in a second layer and poly(butylmethacrylate) in the third layer improve the controlled release of urea. They also observed that the incorporation of this triple polymer fertilizer into soil improved its water-holding capacity, which in turn enhanced nutrient uptake and crop yield.

Biodegradable polymers

These materials have increasingly been used as substitutes of others polymers in agriculture. Devassine *et al.* (2002) divided them in two main groups according to their water vapor permeability, namely, degradable synthetic polymers with a less permeability coefficient (biopols, polylactic acids and polycaprolactone) and modified polysaccharides with a higher permeability coefficient (alginates, starches, agar). Biodegradable polymers have also been used in bioformulations, acting as microbial carriers. These carriers protect microbial inoculants from various stresses and prolong shelf life e.g. calcium alginate gel may protect microbial cells with a concomitant increase in shelf life.

Use of crop residues for smart formulations

Lignocellulosic Straw as Carrier and Coating Material

Low-cost materials such as wheat straw are abundantly available resources in current agricultural systems. These harvesting residues contain lignin, hemicelluloses and cellulose. Cellulose fibrils and lignin impart mechanical strength properties (Panthapulakal and Sain, 2015). Wheat straw contains surface carboxyl, hydroxyl, ether, amino and phosphate, which enhance its reactivity and physicochemical properties, useful in the preparation of adsorbent materials for the treatment of wastewater and slow-release fertilizers.

Cellulose obtained from agricultural residues has been also used in bioformulations as carrier for bacterial inoculants with broad spectrum antifungal activity and suppression of fungal pathogens. In order to further improve their properties as slow-release fertilizers, they could be combined with clay minerals or biochar to reduce their decomposition.

Biochar as carrier and coating material

Harvesting residues, such as straw, may also be used as feedstock for energy producing pyrolysis systems with biochar generation. Considering its physicochemical properties, carbonaceous materials like pyrogenic carbon (biochar) have been widely used as soil ameliorant with several applications in both laboratory and field studies. biochar produced from corncob, banana stalk and pomelo peel displayed an excellent retention ability in holding NH_4^+ associated to the presence of carboxyl and keto groups when the material was prepared at 200°C , suggesting that this material could be used as a slow-release carrier for N.

The use of biochar as carrier for smart fertilizers could be highly beneficial, as it combines nutritional benefits for plants with improvement of many other soil functions due to the addition of biochar itself. In particular, biochar addition to soils has positive effects on water-holding capacity as well as C sequestration. However, biochar properties vary widely depending on feedstock and production conditions

(Wiedner *et al.*, 2013). Thus, the use of these kinds of formulations presents new challenges related to the optimal combination of carrier materials and inoculants. Considering the varying properties of carrier materials here reviewed and the variety of potential utilization for smart fertilizers designs, more research is needed for their development.

CONCLUSION

Advances in the application of biotechnology and nanotechnology have the potential to facilitate improved nutrient management and use efficiency in agroecosystems. Smart fertilizers based on slow-/controlled-release and/or carrier delivery systems have been shown to improve crop yields, soil productivity and lower nutrient loss compared with conventional fertilizers. Several materials such as clays, nanoclays, nondegradable and degradable polymers and agricultural wastes are suitable for the development of smart fertilizers by acting as carrier matrices for nutrients and bacterial inoculants. Future research should continue to explore and evaluate the composition, manufacture and agronomic and environmental performance of various smart fertilizers, especially those that utilize organic waste materials. It is suggested that lignocellulosic organic waste, such as straw after chemical, physical, or thermal transformations may be an excellent carrier or coating material for fertilizer formulations. Such organic wastes occurring as harvesting residues in agricultural systems should be used in the sense of a circular economy to create innovative fertilizers from natural materials, which are urgently needed to ensure sustainable intensification of agricultural systems.

REFERENCES

- AAPFCO, (1995). Official Publication No. 48. Published by Association of American Plant Food Control Officials. Association of American Plant Food Control Officials (AAPFCO). Inc. West Lafayette, Indiana, USA.
- Arora, N.K., Khare, E. and Maheshwari, D.K. (2010). Plant Growth Promoting Rhizobacteria: Constraints in Bioformulation, Commercialization and Future Strategies. In: Plant Growth and Health Promoting Bacteria. [Maheshwari, D.K. (ed)], Springer-Verlag, Berlin, pp 97-116.
- Borie, F., Rubio, R. (2003). Total and organic phosphorus in Chilean volcanic soils. *Gayana. Bot.* 60: 69-78.
- Burges, H.D. and Jones, K.A. (1998). Formulation of microbial biopesticides: beneficial microorganisms, nematodes and seed treatments. Kluwer Academic Publishers, Dordrecht, p 411.
- Chabbi, A., Lehmann, J., Ciais, P., Loescher, H.W., Cotrufo, M.F., Don, A., San Clements, M., Schipper, L., Six, J., Smith, P., Rumpel, C. (2017). Aligning agriculture and climate policy. *Nat. Clim. Change.* 7: 307-309.
- Chalk, P.M., Craswell, E.T., Polidoro, J.C., Chen, D. (2015). Fate and efficiency of ¹⁵N-labelled slow and controlled release fertilizers. *Nutr. Cycl. Agroecosyst.* 102: 167-178.
- Cui, H., Jiang, J., Liu, Q. (2011). On plant nutrition smart delivery systems and precision fertilization. *Acta Metall Sin.* 17: 494-499.
- Dawson, C.J., Hilton, J. (2011). Fertilizer availability in a resource-limited world: production and recycling of nitrogen and phosphorus. *Food Policy.* 36: S14-S22.
- Devassine, M., Henry, F., Guerin, P., Briand, X. (2002). Coating of fertilizers by degradable polymers. *Int. J. Pharm.* 242: 399-404.
- Elser, J., Bennett, E. (2011). Phosphorus cycle: a broken biogeochemical cycle. *Nature.* 478: Pp.29-31.
- EPA (2007). Nanotechnology white paper. Report EPA 100/B-07/001, U.S. Environmental Protection Agency (EPA), Washington, DC.
- Egamberdieva, D., Adesemoye, A.O. (2016). Improvement of Crop Protection and Yield in Hostile Agroecological Conditions with PGPR-based Biofertilizer Formulations. In: Bioformulations: For Sustainable Agriculture. [Arora, N.K., Mehnaz, S., Balestrini, R. (Eds.)], Springer, India, pp. 199-211.
- FAO (2018). World fertilizer trends and outlook to 2020. Food and Agriculture Organization of the United Nations, Rome, Italy. P. 1-38.
- Ghormade, V., Deshpande, M.V., Paknikar, K.M. (2011) Perspectives for nano-biotechnology enabled protection and nutrition of plants. *Biotechnol. Adv.* 29: 792-803.
- International Fertilizer Association (2016). Nutrient Management Handbook. Published by International Fertilizer Association, Paris, France. Pp. 1-44.
- Junejo, N., Khanif, M.Y., Hani, M.M., Yunus, W.M.Z., Dharejo, K.A. (2011). Role of inhibitors and bio-degradable material in mitigation of nitrogen losses from fertilized lands. *African J. Biotechnol.* 10: 3504-3514.
- Kim, I.Y., Pusey, P.L., Zhao, Y., Korban, S.S., Choi, H. and Kim, K.K. (2012). Controlled release of Pantoea agglomerans E325 for bio-control of fire blight disease of apple. *J. Control Release.* 161: 109-115.
- Mansoori, G.A. (2005). Principles of Nanotechnology: Molecular Based-Study of Condensed Matter in Small Systems. University of Illinois at Chicago, USA, World Scientific Publishing Co., p. 360.
- Manjunatha, S.B., Biradar, D.P., Aladakatti, Y.R. (2016). Nanotechnology and its application to agriculture: a review. *J. Farm. Sci.* 29(1): 1-13.
- Ngo, P.T., Rumpel, C., Doan, T.T., Henry-des-Tureaux, T., Dang, D.K., Jouquet, P. (2014). Use of organic substrates for increasing soil organic matter quality and carbon sequestration of tropical degraded soil (a 3 years mesocosms experiment). *Carbon Manage.* 5: 155-168.
- Panthapulakkal, S and Sain, M. (2015). The use of wheat straw fibres as reinforcements in composites. In: Biofiber Reinforcements in Composite Material. [Faruk, O., Sain, M. (Eds.)], Woodhead Publishing, UK, pp. 423-453.
- Qureshi, A., Singh, D.K and Dwidevi, S. (2018). Nano-fertilizers: A Novel Way for Enhancing Nutrient Use Efficiency and Crop Productivity. *Int. J. Curr. Microbiol. App. Sci.* 7(2): 3325-3335.
- Ladha, J.K., Tirol-Padre, A., Reddy, C.K., Cassman, K.G., Verma, S., Powlson, D.S., Van Kessel, C., Richter, D.B., Chakraborty, D., Pathak, H. (2016). Global nitrogen budgets in cereals: a 50-year assessment for maize, rice and wheat production systems. *Sci. Rep.* 6: 1-9. <https://doi.org/10.1038/srep19355>.

- Lemke, R.L., Zhong, Z., Campbell, C.A., Zentner, R. (2007). Can pulse crops play a role in mitigating greenhouse gases from north American agriculture? *Agron. J.* 99: 1719-1725.
- Loper, S. and Shober, A.L. (2012). *Soils and Fertilizers for Master Gardeners: Glossary of Soil and Fertilizer Terms*. Gainesville: University of Florida. Institute of Food and Agricultural Sciences. <http://edis.ifas.ufl.edu/mg457>.
- Mora, M.L., Alfaro, M., Williams, P., Stehr, W., Demanet, R. (2004). Effect of fertilizer input on soil acidification in relation to growth and chemical composition of a pasture and animal production. *J. Soil Sci. Plant Nut.* 4: 29-40.
- Mastronardi, E., Tsae, P., Zhang, X., Monreal, C.M., De Rosa, M.C. (2015). Strategic role of nanotechnology in fertilizers: potential and limitations. In: *Nanotechnologies in Food and Agriculture*. [Rai, M., Ribeiro, C., Mattoso, L., Duran, N. (Eds.)], Springer, Cham, Switzerland, pp. 25-67.
- Naz, M.Y., Sulaiman, S.A. (2016). Slow release coating remedy for nitrogen loss from conventional urea: a review. *J. Control. Release.* 225(10): 109-120.
- Rodrigo, M. (2011). Deciphering the rhizosphere microbiome for disease-suppressive bacteria. *Science.* 332: 1097-1100.
- Rumpel, C., Baumann, K., Remusat, L., Dignac, M.F., Barre, P., Deldicque, D., Glasser, G., Lieberwirth, I., Chabbi, A. (2015). Nanoscale evidence of contrasted processes for root derived organic matter stabilization by mineral interactions depending on soil depth. *Soil Biol. Biochem.* 85: 82-88.
- Royal Society and Royal Academy of Engineering (2004). *Nanoscience and nanotechnologies: opportunities and uncertainties*. The Royal Society and Royal Academy of Engineering, London, UK.
- Sasson, Y., Levy-Ruso, G., Toledano, O., Ishaaya, I. (2007). Nanosuspensions: Emerging Novel Agro Chemical Formulations. In: *Insecticides Design using Advanced Technologies*. [Ishaaya, I., Horowitz, A.R., Nauen, R. (eds)], Springer, Berlin, pp 1-39.
- Sastry, R.K., Rashmi, H.B., Rao, N.H. (2011). Nanotechnology for enhancing food security in India. *Food Policy.* 36: 391-400.
- Sekhon, B.S. (2014). Nanotechnology in agri-food production: an overview. *Nanotechnol. Sci. Appl.* 7: 31-53.
- Shaviv, A. (2005). *Controlled Release Fertilizers*. IFA International Workshop on Enhanced Efficiency Fertilizers, Frankfurt. International Fertilizer Industry Association Paris, France
- Shukla, S., Hanlon, E.A., Jaber, F.H., Stoffella, P.J., Obreza, T.A. and Ozores-Hampton, M. (2013). Groundwater nitrogen: Behavior in flatwoods and gravel soils using organic amendments for vegetable production. Gainesville: University of Florida Institute of Food and Agricultural Sciences. <http://edis.ifas.ufl.edu/ae400>.
- Smith, P.D., Cai, M.Z., Gwary, D., Janzen, H., Kumar, P., Mc Carl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O. (2007). Agriculture. In: *Climate Change 2007: Mitigation*. [Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.)], Cambridge University Press, Cambridge, UK/New York, pp. 497-540.
- Singh, M.V. (2008). Micronutrient deficiencies in crops and soils in India. In: *Micronutrient deficiencies in global crop production*. Springer, Dordrecht, pp 93-125.
- Subramanian, K.S., Paulraj, C., Natarajan, S. (2008). *Nanotechnological approaches in nutrient management: Nanotechnology applications in agriculture*, TNAU technical bulletin. TNAU, Coimbatore, pp 37-42.
- Tao, S., Liu, J., Jin, K., Qiu, X., Zhang, Y., Ren, X., Hu, S. (2011). Preparation and characterization of triple polymer-coated controlled-release urea with water-retention property and enhanced durability. *J. Appl. Polym. Sci.* 120: 2103-2111
- Tarafdar, J.C., Indira Rathore and Esther Thomas. (2016). Enhancing Nutrient Use Efficiency through Nano Technological Interventions. *Indian J. Fert.* 11(12): pp. 46-51.
- Tesfay, T., Gebresamuel, G. (2016). Agronomic and economic evaluations of compound fertilizer applications under different planting methods and seed rates of tef [*Eragrostis tef* (zucc.) Trotter] in northern Ethiopia. *J. Drylands.* 6(1): 409-422.
- Timilsena, Y.P., Adhikari, R., Casey, P., Muster, T., Gill, H., Adhikari, B. (2015). Enhanced efficiency fertilizers: a review of formulation and nutrient release patterns. *J. Sci. Food Agric.* 95: 1131-1142.
- Trenkel, M.E. (1997). *Controlled-release and Stabilized Fertilizers in Agriculture*. International Fertilizer Industry Association, Paris.
- Trenkel, M.E. (2010). *Slow- and controlled- release and stabilized fertilizers: An option for enhancing nutrient use efficiency in agriculture*. Published by International Fertilizer Industry Association (IFA), Paris, France. P. 1-143.
- Trabelsi, D. and Mhamdi, R. (2013). Microbial inoculants and their impact on soil microbial communities: a review. *Bio Med. Res. Int.* 86: 32-40.
- Umesha, C., Sridhara, C.J. and Kumarnaik, A.H. (2017). Recent forms of fertilizers and their use to improve nutrient use efficiency and to minimize environmental impacts. *Int. J. Pure App. Biosci.* 5(2): 858-863.
- Valkama, E., Virkajarvi, P., Uusitalo, R., Ylivainio, K., Turtola, E. (2016). Meta-analysis of grass ley response to phosphorus fertilization in Finland. *Grass Forage Sci.* 71: 36-53
- Vela ´squez, G., Ngo, P.T., Rumpel, C., Calabi-Floody, M., Redel, Y., Turner, B.L., Condon, L.M., Mora, M.L. (2016). Chemical nature of residual phosphorus in Andisols. *Geoderma* 271: 27-31.
- Wiedner, K., Rumpel, C., Pozzi, A., Maas, R., Steiner, C., Glaser, B. (2013). Chemical evaluation of chars produced by thermochemical conversion (gasification, pyrolysis and hydrothermal carbonization) of agro-industrial biomass on a commercial scale. *Biomass Bioenergy.* 59: 264-278
- Yang, X., Abraham, N.L., Archibald, A.T., Braesicke, P., Keeble, J., Telford, P.J., Warwick, N.J., Pyle, J.A. (2014). How sensitive is the recovery of stratospheric ozone to changes in concentrations of very short-lived bromocarbons? *Atmos. Chem. Phys.* 14: 10431-10438.