Essay

Integrated nutrition management: a key tool for sustainable agriculture

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Abstract

The main challenge faced by agriculture is to meet the growing global demand for food while reducing the negative environmental agricultural impact. Crop nutrition depends mainly on mineral fertilizers, which is a threat to the environment and human health. An alternative to solve this problem is the nutrition management integrated with mineral fertilizers and organic fertilizers to reduce the use of mineral fertilizers while favoring the productivity of crops, as well as the quality of agricultural products and the environment. This review compiles research results focused on integrated nutrition management, as part of the holistic functioning of agroecosystems, in several areas: a) soil quality; b) crop productivity and profitability; c) quality of agricultural products; d) emission of greenhouse gases; and e) nitrogen transfer to water.

Keywords: greenhouse gases, integrated fertilization, sustainable agriculture.

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The world population will grow (in millions) from 7 700 in 2019, to more than 9 700 in 2050 (UNDESA, 2019). Such a growing population requires permanent access to safe, nutritious and sufficient food (FAO, 2019). However, agriculture based on large quantities of agrochemicals and other external inputs, as well as unsustainable food consumption, affect the environment and societies since they lead to human health and social fabric conditions (McKenzie and Williams, 2015). Therefore, sustainable agriculture is necessary, which is defined as agriculture that guarantees profitability, environmental health and social and economic equity (FAO, 2015), which is achieved by harmonizing the elements of agroecosystems with their environment (Gutiérrez *et al*., 2015).

Mineral fertilizers (FMs) have several advantages for use in agriculture: solubility and high and precise and nutrient ratios, and relatively low price. Without the use of FMs, global food production would decrease by 50% (Sarkadi *et al*., 2019), and global consumption of N, P and K is expected to reach 199 Mt in 2023 (IFA, 2018). In soils with low contents of C, N and P available, the application of rational doses of FMs improves the quality of the soil (Omari *et al*., 2017).

Nevertheless, FMs have several harmful effects, which begin with their manufacture, by generating toxic chemicals: gases and wastes that pollute the soil, water bodies and air (Chandini *et al*., 2019). In addition, between 60 and 90% of the mineral fertilization (FM) applied is lost (Bhardwaj *et al*., 2014), for instance, part of N is leached or drained as NO_3, volatilized as NH_3 or N oxides, which causes eutrophication of water bodies, greenhouse effect and acid rain (Liu *et al*., 2014b). Even under ideal conditions, plants use only up to 50% of the applied N, the rest is lost in various ways, it is estimated that 2 to 20% volatilizes, 15 to 25% reacts with organic compounds in the soil and 2 to 10% goes to surface and groundwater (Chandini *et al*., 2019).

The excessive use of FMs harms the organisms involved in the genesis and conservation of the soil, in the availability and recycling of nutrients, and in the control of pests and diseases of plants (Hernández *et al*., 2014), it also causes environmental diseases in humans (Hernández *et al*., 2017) such as methemoglobinemia (associated with the consumption of water with high nitrate content) (Larios *et al*., 2015), asthma, heart problems, etc. (related to acid rain) (WHO, 2018). FMs do not provide the soil with the micronutrients required by plants, but supply cadmium, arsenic and uranium, elements toxic to plant and animal life (Sarkadi *et al*., 2019).

Therefore, the benefits and harms of the use of FMs should be evaluated, in order to apply them appropriately to each agroecosystem, considering the sources, dose, time, place, efficiency of nutrient use and risk assessment (Sarkadi *et al*., 2019). On the other hand, the recovery and conservation of agricultural soils requires, among other practices, the recycling of plant waste, animal manure and sewage sludge (Thangarajan *et al*., 2013), transformed into organic fertilizers (AOs) such as compost (Cp) or vermicompost (Vc), biochar, etc.

AOs benefit soil properties and yields (Masunga *et al*., 2016; El-Naggar *et al*., 2019), improve soil aggregation, aeration, moisture, microbiota, organic carbon (CO) of soil (COS), N, mass, diversity (DM) and microbial activity (AM), cation exchange capacity (CIC) and anion exchange capacity, pH, bulk density (DA), stability and nutrient availability (Bhardwaj *et al*., 2014). In addition, AOs such as Vc contain vitamins, hormones and plant growth promoting enzymes (Doan *et al*., 2015).

However, in crops with high and specific nutritional needs, AOs may not supply sufficient amounts of nutrients at the appropriate time (Hernández *et al*., 2014). As an alternative, FAO (1998) proposed integrated nutrition management (MNI), which consists of the application of FMs + AOs, also legumes, crop residues, industrial by-products and biofertilizers are common ingredients in the MNI, with which soil productivity is improved in a sustainable way (Das *et al*., 2014). With MNI, FMs can be partially replaced and the efficiency of AOs and FMs can be raised (García-Mendivil *et al*., 2014).

Therefore, the objective of this work is to provide researchers, engineers and agricultural producers with information on scientific works in which MNI was tested, to improve the effects of MNI on several areas: soil quality, crop productivity, plant health, quality of agricultural products, environmental impact and economic convenience. The criteria followed to include the works were the following: combined use of AOs and FMs, measurement of effects on any of the six areas subject to this study and age of publication no longer than 10 years. The works were ordered according to the area in which MNI had influence and within each area, the works were grouped based on the specific characteristics in which MNI influenced.

Agricultural soil quality and integrated nutrition management

The agricultural quality of soil (CS) reflects its ability to sustain biological productivity and delves into the soil attributes that influence the interaction of soil with the environment, with the provision of nutrients, with photosynthesis and crop growth (Wilson and Sasal, 2017). In recent decades, the concept of CS has evolved towards the concept of 'soil health', in which the ecological attributes of soil that have implications beyond its ability to produce a particular crop are captured (Bünemann *et al*., 2018).

Particle size, aggregate stability (EA), bulk density (DA), structure (Zornosa *et al*., 2015), texture, depth, hydraulic conductivity, water retention capacity (CRA) and porosity (Navarrete *et al*., 2011; García *et al*., 2012) are among the most important physical properties of the soil. Physical properties indicate how soil accepts, infiltrates, retains and provides water to plants, factors that influence root growth, emergence of seedlings, movement of fauna in the profile and exchange of gases (Etchevers *et al*., 2009).

Chemical attributes, such as total and labile CO, total and mineralizable N, pH, electrical conductivity (CE), CIC, etc., affect the availability and quality of water, the availability of nutrients for plants and microbes and the buffering capacity of the soil (Navarrete *et al*., 2011; García *et al*., 2012). It should be noted that COS is related to soil organic matter (MOS) and in the holistic and preventive approach of sustainable agroecosystems, MOS is fundamental (Gupta *et al*., 2017) because it is a storehouse and source of nutrients, improves soil properties, provides beneficial microbes that make nutrients available, stimulate plant growth and suppress pathogens (Hernández *et al*., 2014; Masunga *et al*., 2016). The biological and biochemical properties of the soil such as C and N of microbial biomass (CBM and NBM), basal respiration (RB), enzymatic activities, DM, AM, etc., indicate early changes in MOS and in nutrient recycling and dynamics (Navarrete *et al*., 2011; Fuentes *et al*., 2016).

In several crops with MNI, improvements in soil fertility have been reported, for example, in the rice system (*Oryza sativa*), wheat (*Triticum aestivum*), with the application FMs + 12 t ha^{-1} of Cp, the availability of N, P, K, Ca and Mg increased, while the pH and the adsorption of Na of the soil decreased, which is explained by the formation of acids, release of Ca and leaching of Na (Sarwar *et al*., 2008). In addition to increasing nutrient content, MNI with fungal residues + FMs buffered soil acidification caused by FMs in rice cultivation (Shi *et al*., 2019).

In the cultivation of soybean (*Glycine max*) and wheat, the application for 21 years of FMs + farm manure (EG) led to better levels of extractable micronutrients (Fe, Mn, Zn and Cu) compared to FM (Choudhary *et al*., 2018). Regarding residual soil fertility, in wheat with MNI (8 t of Cp ha^{-1}), in current (year 1) and residual (year 2) trials, the available P increased 162 and 173%, MOS 108 and 104%, interchangeable Ca 16. 7 and 17. 4% and CIC 15.4 and 17.1%, respectively (Demelash *et al*., 2014). The residual soil fertility of the wheat crop benefited from MNI which included the use of 100% FM + EG + *Azotobacter* + Zn + Mn + Fe (Singh *et al*., 2017).

The MNI of rice-wheat and cotton (*Gossypium hirsutum*) wheat systems, with the inclusion of Cp of municipal residues, DA and penetration resistance improved, and there was no accumulation of heavy metals (zinc, cadmium, chromium, lead and nickel) (Qazi *et al*., 2009). With the inclusion of biochar in MNI, in addition to improving CS, heavy metals are immobilized (Šimanský *et al*., 2019). MNI also improves the biological attributes of soil. Liu *et al*. (2017) tested in rice paddies an index that included the available nutrients, CBM and enzymatic activity involved in the cycles of C, N, P and S and found that with the use of FMs + pig manure, the highest score was obtained (0.85), compared to the control (0.72) and with the FM alone (0.77), FM + green fertilizers (AVs) (0.81) and FM + straw (0.79).

In the cultivation of corn (*Zea mays*), with FM + Vc, the highest improvements in terms of CIC, water availability and P were obtained, this was because the Vc stimulated AM, nutrient mineralization and secretion of enzymes of the roots (Doan *et al*., 2015). The MNI with bokashi, in the cultivation of corn, increased the mycorrhizal colonization (Álvarez-Solís *et al*., 2010) as well as the CBM (Bautista-Cruz *et al*., 2015). The use of Cp + bacterial fertilizer increased the diversity of bacterial and fungal communities in maize (Zhen *et al*., 2014). In bananas (*Musa paradisiaca*), with MNI (recommended 50% FM + 1 250 kg of MO ha^{-1}), bacterial diversity, pH and acid phosphatase activity increased, but as the application of FMs increased, these soil attributes decreased (Sun *et al*., 2018).

Srivastava *et al*. (2012) reported that in citrus plantations the gradual change of FMs to AOs favored DM. With MNI in tomato (*Lycopersicom esculentum*), MOS, labile C (Ren *et al*., 2014) and RB (Hernández *et al*., 2014) increased. Long-term MNI studies show a positive effect on COS and on the physical properties of the soil. In that sense, Cai *et al*. (2019) applied MNI in the rice-wheat system and observed that during the first 10 years the COS increased and then stabilized in the following 15 years. In another study, with the application for more than 40 years of FMs + 15 t ha^{-1} of EG in the rice-wheat system, the CO level was maintained, and some physical properties of the soil were improved, such as DA, hydraulic conductivity and CRA (Pant *et al*., 2018), but the zinc content decreased (Ram *et al*., 2016).

In another work, the MNI with FMs + 5 t ha^{-1} of EG, after 41 years of treatment, increased the size and stability of soil aggregates (Tripathi *et al*., 2014). Through a meta-analysis elaborated with results of research carried out from 1989 to 2016, it was detected that in the rice-wheat system under MNI, the pH increased with respect to the control (without FMs or AOs), by 1.15% in the soil of the rice crop, but in wheat it decreased 0.55%, in addition the COS increased 23.2% and 16.2% with respect to the application of FMs alone in rice and wheat, respectively, the MNI also increased the NBM and the CBM. It should be noted that the effects of MNI were influenced by soil type, since the differences found in pH, NBM and CBM were greater in loamy-clay soil than in clay soil (Sharma *et al*., 2019).

Integrated nutrition management and productivity of agricultural crops

The benefits of MNI on CS help to create sustainable agrosystems (Cai *et al*., 2019), this is maximized in unproductive soils, since the production and application of large quantities of AOs would require covering high labor costs and sometimes the availability of raw materials is limited (Wang *et al*., 2015). In the cultivation of corn, with the application of 50% FM + AOs (compost, bokashi and worm humus), the yield increased by 3.8, 12.7 and 11.5% compared to 100% FM, while with 100% FM + AOs, the increase was 17.7, 21.9 and 30.5%, respectively (Álvarez-Solís *et al*., 2010).

In another study of MNI, some parameters related to crop yield were evaluated in maize plants, and the highest values of plant height, dry weight, leaf area index, photosynthesis and stomatal conductance appeared with the application of EG + FMs (Efthimiadou *et al*., 2010). Also, the absorption of nutrients (N, P, K, Zn, Fe and Mn) increased with the MNI (FMs + EG + solubilizing bacteria of P + *Azotobacter* + Zn + Fe + Mn) (Singh *et al*., 2017). In mustard cultivation, the radius, index and duration of the leaf area, the net assimilation rate (net exchange of CO_2 per unit of leaf area), chlorophyll, photosynthesis and growth of the crop were higher with MNI (75% FM + Vc at 2.5 t ha^{-1}) compared to that obtained with 100% FM (Mondal *et al*., 2017).

On the other hand, in the tomato cultivation with MNI (60% FM + Cp, Vc or AVs), yields of fruits, height and dry weight of plants similar to those obtained with 100% FM were obtained (Hernández *et al*., 2014; Ilupeju *et al*., 2015). With the addition of biofertilizers in the MNI, the improvements in yields are even greater (Chatterjee *et al*., 2014; Verma *et al*., 2015); for instance, MNI with Cp inoculated with *Trichoderma* leads to a yield 43.8% higher than with FM (Abedin *et al*., 2018). It has been observed that the application of poultry manure + N mineral in the cultivation of chili (*Capsicum annuum*) increased the soil temperature, which accelerated the enzymatic reactions related to the ripening of the fruits (Macías *et al*., 2012).

A 25-year evaluation (1991 to 2015) with the application of EG + FM showed that the average yields of wheat and corn (1.6 and 5.8 t ha^{-1}) were higher than with FM (0.97 and 2.65 t ha^{-1}), respectively. In another study, with 30 years of MNI of soybean and wheat, yields were higher than with FM; however, even with MNI, yields declined over time, possibly because the available P, K and Zn decreased (Bhattacharyya *et al*., 2008).

MNI in citrus maintained long-term productivity (Srivastava *et al*., 2012). A meta-analysis of the rice-wheat system detected the increase in crop yields with MNI, by 2.5, 29.2 and 90.9% over FM, AOs and control, respectively (Sharma *et al*., 2019). Another meta-analysis showed that FM + straw increases crop yields 5.1% more than FM alone (Xia *et al*., 2018).

Integrated nutrition management and plant health

The quality of plant nutrition determines their histological and morphological characteristics, as well as their resistance and ability to suppress pathogens (Gupta *et al*., 2017), but the excessive and unbalanced application of FMs makes plants more susceptible to diseases (Wu *et al*., 2015). On the other hand, good plant health is favored with the existence in agroecosystems of microbial competition, hyperparasitism, antibiosis, acquired and induced systemic resistance in crops, inactivation of pathogen proliferation and influence of the physicochemical properties of AOs (Mehta *et al*., 2014).

The MNI with balance of AOs and FMs has shown that it confers good conditions for DM, improves plant nutrition, ecosystem resilience and competition against pathogens (Sun *et al*., 2018). However, such results do not always occur (Postma and Schilder, 2015), this because the suppression of diseases depends on multiple and complex interactions of the soil components of different crops, management practices, fertilizers and environments (Sun *et al*., 2018).

For example, a trial of late blight in tomato registered a lower incidence (13.8%) with 75% FM + Vc (4 t ha^{-1}) + biofertilizer compared to FM alone (31.6%) (Chatterjee and Khalko, 2013). In chrysanthemum, Pinto *et al*. (2013) studied the effect of MNI with different AOs on *Fusarium* suppression and found that suppression was greater as the dose of Cp was increased, but adding biofertilizer, fish hydrolysate, chitosan or *Trichoderma* had no effect on the disease, the above suggests that suppression depends on the interaction of diverse chemical and microbiological factors.

In bananas, the level of suppression of F*usarium* and CS had a negative correlation (r = -0.92, $p<$ 0.01); 85.9% of the variance was explained by the supply of P and K (54.3%) and by the AM (31.6%). The supply of P and K was favored with high doses of MO (500 or 750 g $plant^{-1}$) + FM at 100 or 50%, while the AM was increased with 25% FM + MO. With 50% FM, even without MO, AM was stimulated, but with 100% FM without application of MO, the incidence of the disease increased (Sun *et al*., 2018).

Integrated nutrition management and quality of agricultural products

Nutrition management affects the quality of crops. A study in wheat recorded that with MNI, in plants the content of N, Ca and Mg was doubled and the P quadrupled (García-Medívil *et al*., 2014), in addition, in another study, the increase of protein in grain was recorded (Singh *et al*., 2017). In tomato cultivation, AOs without FM generated less N in leaves and fruits, while with MNI, good quality fruits were obtained in terms of size, firmness, soluble solids, titratable acidity, macro and micronutrients (Hernández *et al*., 2014), in other research with MNI of tomato, lycopene (35. 5%), antioxidant activity (24 to 63%), defense enzymes (11 to 54%) and vitamin C were also increased (Ilupeju *et al*., 2015; Verma *et al*., 2015).

In the cultivation of chili (*Capsicum* spp.), capsaicin and ascorbic acid in fruits increased with the application of 75% N of neem cake + 25% N of urea, but with 25% N of EG + 75% N of urea, capsaicin levels decreased (Pariari and Khan, 2013). In chili cultivation, the application of Vc alone or with FM increased acidity, protein, carotenes, lycopenes and vitamin C in fruits, but Ca was higher with the control than with MNI (Das *et al*., 2016b; Premamali *et al*., 2019).

The MNI of mustard (*Brassica campestris*) augmented the content of chlorophyll, sugar and proline (Mondal *et al*., 2017), this was thanks to the improvement of chlorophyll biosynthesis and photosynthesis, this was due to the fact that MNI with Vc and *Azotobacter* increased the fixation and availability of N, the production of plant growth promoting substances and the absorption of nutrients (Singh *et al*., 2014). In the cultivation of gladiolus (*Gladiolus grandiflorus*), the use of Vc + Cp inoculated with *Trichoderma* + 25% FM improved the shoot time, planting period, number and weight of corms, length of spikes and rachis, number of spikes and florets (Akter *et al*., 2017).

With the MNI in basil (*Ocimum basilicum*), the oil yield (methyl chavicol and linalool) increased, compared to the AOs or with the FM (Anwar *et al*., 2005) and in the nopal cladode (*Opuntia ficus-indica*), the zinc and boron content increased, but that of Mn was higher with the FM (Santiago-Lorenzo *et al*., 2016).

Integrated nutrition management and influence of C and N on the environment

Globally, COS reserves are depleted in agroecosystems (Lal, 2018). Organic farming benefits the environment and human health but could exacerbate greenhouse gas (GEI) emissions through increased land occupation to compensate for declining yields (Smith *et al*., 2019). On the other hand, inadequate agricultural application of N causes environmental and health problems (Liu *et al*., 2014b). As an alternative to this problem, MNI improves soil C capture (CCS), mitigates GEI emissions (Hua *et al*., 2014) and N losses to the environment (Ren *et al*., 2014). However, the C of crop residues on the soil surface stimulates AM, so COS is transformed into CO_2 or CH_4 through aerobic and anaerobic respiration (Liu *et al*., 2014a).

In contrast, burying straw increases CCS and N retention, thereby reducing GEI emissions and N losses (Yang *et al*., 2019). This demonstrates the need for proper agronomic management. In a study in tomato, MNI (75% FM + 4 t ha^{-1} Vc + biofertilizer) improved the efficiency of N use (Chatterjee *et al*., 2014). MNI also decreased runoff water and leaching of NH_4^+ and NO_3^- (Doan *et al*., 2015), in addition, it favored the reproduction of beneficial microbes, COS and the fixation and use of N (Ojo *et al*., 2015). In basil cultivation, CBM and NBM were higher in soils with MNI with Vc, compared to those of FM.

This is due to the residual effect of Vc on CCS, due to the high production of biomass, rhizodeposition of carbonaceous materials and detached tissue (Anwar *et al*., 2005). In rice paddies, MNI with balance in the proportions of FMs and AOs improved CCS and C mineralization (MC), but the overuse of AOs or FMs produced the reverse effects (Shi *et al*., 2019). In winter wheat-summer corn rotations, the FM (N and P) applied for nine years did not alter the labile C, soil microbiota, or MC; while the use of straw + FMs increased labile C, microbes related to phospholipids and MC (Li *et al*., 2018a).

In wheat-soybean and wheat-corn rotations under MNI for nine years, soil CO and N had increases of between 14 and 37%, this thanks to the fact that the C and N of AOs are stored in recalcitrant fractions associated with soil minerals (Li *et al*., 2018b). With 46 years of MNI in the maize-wheat system, CBM, RBS, MC and microbial ratio increased compared to FM (Kaur *et al*., 2019). A meta-analysis focused on the MNI with the use of crop residues detected that with straw return, COS increased 14.9% and the absorption of N by the crops grew 10.9%, this thanks to the microbial immobilization of N.

In rice paddies, MNI reduced losses of N_2O (17.3%), N leaching (8.7%) and runoff (25.6%). However, in non-flooded crops, with the use of FM + straw, N_2O emissions (21.5%) and NH_3 emissions (17.0%) increased, this due to increased nitrification-denitrification and urease activity in the soil. Emissions of NH_3 and N_2O decreased as the straw/C ratio and soil clay content were higher; but globally, straw return increases losses of N-NH_3 (Xia *et al*., 2018).

In corn-soybean-wheat systems, depending on nutritional management, CO_2 emission had the following trend: FM + pig manure > FM + corn straw > FM (Li *et al*., 2013). Therefore, in order to achieve balance of the effects of MNI, the specific characteristics of the agroecosystems where it is applied must be considered (Liu *et al*., 2014a).

Economic convenience of integrated nutrition management

Any agronomic technology that improves the soil will be attractive to farmers only if it is economically profitable. MNI has demonstrated this characteristic. For example, in wheat, MNI (6 t of Cp ha^{-1} + 34.5 kg of N ha^{-1}) improved CS and generated US $8.44 for each US $1.00 of additional investment in AOs and FMs (Demelash *et al*., 2014). In a long-term study in soybean-wheat rotations, in years 1 to 5 and 26 to 30 of cultivation, the benefit:cost ratio (B:C) for soybeans was higher with MNI than with FM alone, which showed that in the long run MNI is more profitable, while FM generated no profits or losses (Bhattacharyya *et al*., 2008).

In rice-wheat and cotton-wheat, MNI maintained accumulated net benefits, B:C and competitive net returns (Qazi *et al*., 2009) and after 41 years of MNI, the economic yield of rice increases 9.34% (Sharma *et al*., 2019). In several crops, MNI has shown its economic effectiveness, as it raised the productivity and profitability of wheat (Singh *et al*., 2017), generated the highest net return, with a B:C of 1:3.5 in the cultivation of onion (*Allium cepa*) (Jamir *et al*., 2013), while in tomato, it maximized the B:C (2.26 to 2.78) (Abedin *et al*., 2018). However, in corn, in the short term (2 years), 100% FM generated higher net profit than MNI (with 50% FM) and the highest B:C occurred with the control (without FMs and without AOs) (Hashim *et al*., 2015).

Conclusions

MNI is useful for sustainable agricultural management in several areas: a) it improves the quality of soil, water, air and biodiversity, in addition, it helps to mitigate global warming, this provided that practices are implemented to capture CO_2 derived from the increase in biological activity; b) it raises the quality of food and benefits the health of consumers and c) it maintains competitive yields and raises the economic efficiency of agroecosystems. Multiple studies agree that MNI can decrease FM by 25 to 50%, without affecting yields, with the improvement of the quality of agricultural products and the environment.

However, the benefits of MNI generally occur in the long term and depend on the doses, properties, times and methods of application of organic fertilizers and mineral fertilizers, as well as interactions with the components of the cultivation soil, management and environment. Therefore, the conditions of each agroecosystem and its environment should be considered to implement nutrition practices that lead to sustainability.

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