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**Review Articles**



**Research Articles**

**Review Article**

# CAN ORGANIC MATERIALS SUPPLY ENOUGH NUTRIENTS TO ACHIEVE FOOD SECURITY?

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## ABSTRACT

Developing countries in the world are in tremendous pressure to increase food production to achieve food security of their ever-increasing polulation. Increase in food production is not possible without adequate use of high-yielding inputs such as varieites, water, nutrients and good crop management. Of all inputs, nutrients, whether from inorganic or organic sources, are crucial to increase crop yields, improve soil fertility, and achieve food security. However, several myths exist surrounding the use of inorganic (chemical) fertilizers, and organic materials or organic fertilizers. The objectives of this paper are: (i) to clarify some of the myths, or misconceptions by providing scientific facts, or realities so that the applications of appropriate amounts of inorganic, or organic fertilizers, either alone, or in their combination can be advised to farmers, and (ii) to propose alternative solutions to increase on-farm biomass production to use as organic inputs for improving soil fertility. Several myths and realities about the use of inorganic fertilizers and organic materials/fertilizers are discussed. Considering the current global situation of availability of organic materials, it is advised to apply nutrients from inorganic and organic sources at 75:25 ratio instead of full amount through organic materials only. Further, organic nutrients alone are not sufficient to increase crop yields and achieve food security. The review identifies a new and advanced concept of Evergreen Agriculture (an extension of Agro-forestry System), which has potential to improve on-farm soil fertility and meet crop nutrient demand by increasing the supply of organic materials, increase crop yields, sequester carbon and mitigate emissions, provide fodder for livestock, and finally achieve food security of ever-increasing global population. Evergreen Agriculture has been widely adapted by tens of millions of farmers in several African countries, and the review proposes for evaluation and promotion of such technology also in countries in South Asia, including Nepal.

**Key words:** Evergreen agriculture, organic materials, organic and inorganic fertilizers, Myths and realities, plant nutrient content, soil fertility

## INTRODUCTION

It is a widely recognised fact that small and poor farmers in all countries of the world lack resources to purchase high-yielding inputs such as chemicalfertilizers (also called inorganic/mineral/synthetic fertilizers), or other chemical inputs and water, and hence rely on the inputs in whatever quantities already available intheir farm. One of the maininputs required for high-yiellding crops are nutrients which are either available in varying amounts (from low to high) in soil (i.e., indigenous nutrients) and/or shlould be applied through external sources (i.e., either inorganic or organic). Small or subsistence farmers aimimg for low yields can rely onorganic inputs such as farm yard manure (FYM), composts, or crop wastes and residues in whatever amounts they are available in their farm (Timsina et al., 1991). However, such inputs contain very low amounts of nutrients which can only support very low-yielding crops, vegetables or fruits, a typical characteristic of the subsistence farming system (BARC, 2012). For transitioning from subsistence to commercial agricultureand to achieve high yields and high income from crops, vegetables or fruits, application of high-yielding inputs, particularly inorganic fertilizers is necessary. If sufficient amounts of nutrients, whether from inorganic or organic alone, or a combination of both sources, are not applied to plants, high yields may not be possible and transitioning to commercialization of agriculture will be a dream only.

Inorganic fertilizers are applied to the soil to supplement or substitute for biological functions that are considered inadequate or inefficient for achieving the required levels of production. As per FAO's revised projection regarding world agriculture, global agricultural production in 2050 should be60% higher than in 2005/2007 (Alexandratos and Bruinsma, 2012). To close this gap, total crop production would need to increase even more from 2006 to 2050 (i.e., an 11% larger) than it did in the same number of years from 1962 to 2006 (Searchinger et al., 2014). The bulk of the projected increasein crop production will come from high yields, which normally demand high fertilizer application rates, and will lead to an increase in fertilizer use (Alexandratos and Bruinsma, 2012). Erisman et al. (2008) reported that over 48% of more than 7 billion

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people are living today because of increased crop production made possible by applying fertilizer nitrogen (N). However, fertilizers being chemicals can potentially disturb the natural functioning of the soil and may also affect the output of other ecosystem services. The challenge ahead is to manage fertilizers (inorganic and organic) and soil in such a way that not only food demands are continuously met, but soil also remains healthy to support adequate food production with minimal environmental impact.

While inorganic fertilizers are crucial to increase crop yields, the reality across all countries in the word, especially the tropical and sub-tropical ones, is that the soil-derived and organic sources of nutrients may not be sufficient for high yield, but at the same time externally-applied inorganic fertilizers are generally not affordable by small-scale subsistence farmers. With low inputs, high production is not possible; country's food security can not be achieved; and hence poverty will be widespread. It is the responsibility of government policy makers and planners to develop suitable schemes to provide incentives or subsidies to smallholder farmers for their access to credit and fertilizers. While role of nutrients, whether organic or inorganic, for increased crop production is universally recognised, there seem to be several myths or misconceptions of using inorganicand/or organic sources of nutrients. Some sectors of the society, particularly those activists or advocates influenced by INGOs or NGOs, many researchers and extensions workers, and even the governemnt policy makers wrongly advised by their advisers claim that continuous use of the chemical fertilizers adversely affects soil quality and decreases the soil and crop productivity. These claims however have no sufficient scientific basis and any decline in soil or crop productivity maybe due to over- or mis-use of chemical fertilizers. Hence, the objectives of this paper are: (i) to clarify some of the myths or misconceptions by providing scientific facts and realities so that the applications of appropriate amounts of inorganic or organic fertilizers either alone or in their combination can be advised to farmers, and (ii) to propose alternative solutions to increase on-farm biomass production for use as organic inputs for maintaining or improving soil fertility. Such clarifications and alternative solutions will help planners and policy makers of any country to develop policies to promote for the rationale use of inorganic and/or organic nutrient inputs to achieve food security and get rid of poverty of their ever-increasing population.

**Terms and Concepts**

To help understand the concepts, it is important to understand the differences between organic farming, organic materials, organic fertilizers, organic nutrients and bio-fertilizers.

**Organic farming**: It is a form of agriculture that deliberately follows a set of management practices, which exclude the use of chemical fertilizers and other chemical inputs such as herbicides and pesticides, and instead uses crop rotations, mineral-bearing rocks, and organic materials, organic fertilizers or organic nutrients to supply to plants.

**Organic materials**: These generally refer to undecomposed crop residues and plant biomass, or products derived from plants and animals. Some of the organic materials available and used as organic sources of fertilizers in Nepal include i) agricultural wastes such as crop residues (including rice and wheat straw, maize stover, legume leaves and residues, etc.), rice hulls, wheat chaffs, weeds and grasses in farms, homesteads and farmsteads, biochars, etc., ii) biodegradable wastes, including kitchen and market wastes, fruits and vegetables peelings, and biosolids, etc., iii) FYM and litters such as cattle manure, poultry manure, farm composts, etc., and iv) Forest and grasslands wastes, such as tree leaves, branches and twigs, shrubs and herbs underneath trees, roadside and community grasses and weeds, etc.

**Organic nutrients:** These refer to nutrients contained in organic materials, organic fertilizers and biofertilizers.

**Organic fertilizers**: These refer only to decomposed or partially-decomposed plant or animal materials used as a source of nutrients for crops. These also refer to small-sized pellets or granules developed from processing of organic materials.

**Bio-fertilizers**: These refer to microbial amendments of organisms such as *Rhizobia* or *Azospirilium*, bacteria promoted to stimulate biological $N_2$ fixation, or *Trichoderma*, a fungus promoted to hasten decomposition of organic materials.

**Benefits of organic materials**: Organic materials are often promoted for improving the physical, chemical, biological and microbial properties of soils. Claimed improved physical properties include improved soil structure and aggregation, improved water holding capacity, and better drainage, while claimed improvement in biological properties include improved microbial populations on biological activity. Claimed benefits on soil chemical properties include higher nutrient holding capacity, such as through increased cation exchange capacity, and increased ability to resist changes in soil pH (Buresh and Dobermann, 2010). Changes in soil physical properties can improve the medium for plant growth under well-drained, aerobic condition but such changes are usually not relevant for submerged rice soils, which during land preparation are typically flooded through puddling which destroys soil structure (Ponnamperuma, 1972). Submergence or flooding tends to buffer pH near neutrality, and reduces the decomposition of native SOM, or mineralization of SON as compared to aerobic soils. In addition, the puddling of rice soils reduces downward movement of water thereby reducing the need for greater nutrient-holding capacity of soil to reduce loss of nutrients by leaching (Ponnamperuma, 1972).Likewise, organic materials are generally more likely to stimulate the activity of aerobes (e.g., *Azospirilium* or *Trichoderma*) in well-drained or aerobic soils than the predominant anaerobic bacteria in submerged soil (Mamaril et al., 2009).

**Myths and realities of organic and inorganic fertilizers**: Some of the myths and realities of organic and inorganic fertilizers are illustrated below. Most of the benefits associated with organic fertilizers seem to be the myths and mostly based on guesses, perceptions, or prejudices, or for political motives, while the realities associated with them are based on the proven scientific evidences:

**Alteration of soil physical and chemical properties**: A common myth is that the organic sources of fertilizers improve soil physical properties such as soil structure and water holding capacity of all soils while the chemical fertilizers destroy the soil physical properties (Mamaril et al., 2009). The reality is that the organic materials, particularly when used as soil cover or mulch, can improve soil physical properties of only aerobic soils through improved water retention, reduction in soil crusting, increased soil porosity, and reduced erosion. Since flooded rice fields are puddled during land preparation intentionally destroying the soil structure, improvements of soil physical properties are of little significance for those fields. However, improvements in soil physical properties may be of importance for direct-seeded rice established without puddling, or for non-puddled transplanted rice which are now being promoted through conservation agriculture(CA) in South Asia (Buresh and Dobermann, 2010; Gathala et al., 2015). In CA, soil is tilled to a minimum extent and crop residues are retained in the soil so as to help build up of SOM (Gathala et al., 2015, 2016).

On the other hand, a widely perceived and politically motivated claim is that chemical fertilizers deteriorate soils by altering their physical properties and making them acidic (Mamari, 2004). The general perception by policy makers, researchers and extension workers is that the declining soil or crop productivity is due to soil degradation (structural change and acidification, etc.) with use of inorganic fertilizers, whether in small or large quantities. There are no scientific evidences that have proven that the chemical fertilizers, when applied in optimum rates for high yield, destroy soil structure or soil water holding capacity. Chemical fertilizers per se do not deteriorate soils by changing soil texture or making soils acidic. Until and unless fertilizer N acidifies the soil to $pH < 5$, the application of N fertilizers at optimal rate generally has a positive effect on soil biota. It is only when they are continuously applied in excessive amounts (such as practised in China) they may change soil texture and result in soil acidification. In Nepal, the use of chemical fertilizers is too low, and thus acidification from use of inorganic fertilizers should not be an issue.

**Supply of nutrients as per crop demand**: Another widely propagated myth by the advocates of organic fertilizers is that organic materials (manures, crop residues, green manures, biofertilizers, etc.) can provide the required quantity of essential plant nutrients for crops. The reality is that organic materials contain minimal macro- and micro nutrients compared to inorganic fertilizers (Tables 1-4). Further nutrient value of organic materials, particularly that of FYM and composts, is highly variable, and often more variable than that of crop by-products such as residues (rice straw or maize stover or hulls/husks, etc.). The animal's diet, the use and type of bedding material, manure age, and how it was stored are factors that affect manure nutrient value; these factors can vary seasonally on and among farms, and regionally or on a larger geographic scale. Thus, if the nutrients required for high yields are to be supplied through organic sources only, their voluminous amounts would be required to supply required amounts of nutrients. Some of the nutrients will be available through soil organic matter (SOM), while the remaining should be supplied through organic or inorganic sources (see details below). The exception is that organic materials, especially crop residues (e.g., rice residues), can supply (recycle) considerable potassium (K), sometime even in excess of crop needs. The integrated use of inorganic fertilizers with organic materials should consequently account for this supply of K from organic materials (Timsina et al., 2013).

**Table 1. Nutrient compositions (%) of some commonly used chemical fertilizers in Asia**

| Fertilizer | Chemical formula | Nutrient content (%) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | N | $P_2O_5$ | $K_2O$ | S | Ca | Mg | Mn | Zn | B | Ca | Mo |
| Urea | $CO(NH_2)_2$ | 46 | | | | | | | | | | |
| Ammonium sulphate | $(NH_4)_2SO_4$ | 21 | | | 24 | | | | | | | |
| Triple super phosphate | $Ca(H_2PO_4)_2$ | | 46 | | 1 | 14 | | | | | 14 | |
| Single super phosphate | $Ca(H_2PO_4)_2+CaSO_4.2H_2O$ | | 18 | | 12 | 20 | | | | | 20 | |
| Diammonium phospahte | $(NH_4)_2HPO_4$ | 18 | 46 | | | | | | | | | |
| Muriate of phosphate | KCl | | | 60 | | | | | | | | |
| Magnesium sulphate | $MgSO_4$ | | | | 13 | | 9.5 | | | | | |
| Dolomite | $CaCO_3.MgCO_3$ | | | | | | 12 | | | | | |
| Dolomitic lime | $CaCO_3.MgCO_3$ | | | | | 17 | | | | | | |
| Zinc sulphate (hepta) | $ZnSO_4.7H_2O$ | | | | 18 | | | | 23 | | | |
| Zinc sulphate (mono) | $ZnSO_4.H_2O$ | | | | 18 | | | | 36 | | | |
| Zinc sulfate | ZnO | | | | | | | | 35 | | | |
| Gypsum | $CaSO_4.2H_2O$ | | | | 18 | 33 | | | | | 33 | |
| Boric acid | $H_3BO_4$ | | | | | | | | | 17 | | |
| Manganese sulphate | $MnSO_4.H_2O$ | | | | 21 | | | 36 | | | | |
| Calcium chloride | | | | | | | | | | | 36 | |
| Ammonium molybdate | $(NH_4)6Mo7O24.2H_2O$ | 6.8 | | | | | | | | | | 54 |

P*2.29=$P_2O_5$; K*1.2=$K_2O$; Source: BARC (2012); Mamaril et.el. (2019)

**Table 2. Nutrient concentrations (%) of some commonly used organic materials in Asia**

| Organic materials | Nutrient content (%) | | | |
|---|---|---|---|---|
| | N | $P_2O_5$ | $K_2O$ | S |
| Cowdung (Fresh 60% MC) | 0.50 | 0.34 | 0.6 | - |
| Cowdung (Decomposed 30% MC) | 2.06 | 2.29 | 1.92 | 0.13 |
| Farm yard manure (70% MC) | 1.00 | 1.90 | 2.04 | 0.56 |
| Poultry manure (55% MC) | 2.50 | 1.28 | 0.9 | 1.10 |
| Duck manure | 2.15 | 2.59 | 1.38 | - |
| Goat manure | 2.00 | 3.41 | 2.94 | - |
| Swine manure | 2.76 | 6.05 | 1.764 | - |
| Compost (rural 40% MC) | 0.75 | 1.37 | 1.2 | - |
| Compost (urban 40% MC) | 1.50 | 1.37 | 1.8 | - |
| Mustard oilcake (15% MC) | 5.00 | 4.12 | 1.44 | - |
| Linseed oilcake (15% MC) | 5.50 | 3.21 | 1.44 | - |
| Sesame oilcake (15% MC) | 6.20 | 4.58 | 1.44 | - |
| Groundnut oilcake | 7.00 | 3.44 | 1.56 | - |
| Bone meal (raw, 8% MC) | 3.50 | 20.61 | - | - |
| Bone meal (steamed, 7% MC) | 1.50 | 22.90 | - | - |
| Dried blood (10% MC) | 11.00 | 1.10 | 0.70 | - |
| Fishmeal (10% MC) | 7.00 | 3.50 | 1.00 | - |

P*2.29=$P_2O_{5;}$ K*1.2=$K_2O$; Source: BARC (2012); Mamaril et.el. (2019)

**Table 3. Nutrient contents (%) of some commonly used green manure crops and crop residues in Asia**

| Fertilizer | Scientific name | Moisture (%) | Nutrient content (%) | | | |
|---|---|---|---|---|---|---|
| | | | N | $P_2O_5$ | $K_2O$ | S |
| Dhaincha | *Sesbania* sp. | 80 | 2.51 | 0.92 | 0.92 | 0.20 |
| Mung bean | *Vigna radiata* | 70 | 0.80 | 0.46 | 1.15 | 0.30 |
| Black gram | | 70 | 0.80 | 0.46 | 1.15 | 0.30 |
| Cowpea | *Vigna unguiculata* | 70 | 0.70 | 0.34 | 1.15 | - |
| Soybean | *Glycine max* | | | -- | -- | |
| Pea | *Pisum sativum* | | 1.97 | | | |
| Pigeon pea | *Cajanus cajan* | | | | | |
| Sunhemp | *Crotolaria juncea* | 70 | 0.70 | 0.27 | 1.15 | - |
| Rice straw | *Oryza sativa* | 30 | 0.58 | 0.23 | 3.16 | - |
| Wheat straw | *Triticum aestivum* | 20 | 0.50 | 0.69 | 2.06 | - |
| Maize stover | *Zey mays* | 15.5 | 0.59 | 0.71 | 3.00 | - |
| Sugarcane leaves | | 20 | 1.00 | 1.15 | 3.21 | - |
| Rice hull | *Oryza sativa* | 15 | 0.31 | 0.16 | 0.85 | - |
| Coconut husk | | - | 1.75 | 0.27 | 2.06 | - |
| Banana stem | | - | 1.00 | 1.05 | 19.42 | - |
| Leucaena | *Leucaena leucocephala* | | 4.29 | 0.44 | 3.14 | - |
| Azolla | *Azolla sp* | | 3.68 | 0.46 | 0.34 | - |
| Acacia | *Acacia arabica* (leaves) | | 2.61 | 0.39 | 2.75 | - |

P*2.29=$P_2O_5$; K*1.2=$K_2O$; Source: BARC, 2012

**Table 4. Amount of N fixed (kg/ha) by some common aerobic and anaerobic N-fixing organisms and tree legumes grown in Asia and Africa**

| | N-fixing bacteria | Amount of N fixed (kg/ha)[1] |
|---|---|---|
| Aerobic | *Azospirillium* sp. | 20-40/season |
| | *Klebsiella* | 32/year |
| | *Anabaena* (Cyanobacter/Blue green algae) | 15-45/crop |
| | *Nostoc* (Cyanobacter/Blue green algae) | 15-45/crop |
| | *Enterobacter* | 32/year |
| | *Achromobacter* | 32/year |
| | *Klebsiella* | 32/year |
| | *Cynobacter*/Blue green algae | 15-45/crop |
| Tree and perennial legumes | *Gliricidia sepium* | 212/year |
| | *Acacia anguistissima* | 122/year |
| | *Leucaena collinsi* | 300/year |
| | *Cajanus cajan* | 34-85/crop |
| | *Sesbania sesban* | 84/crop |

Source: Akinnifesi et al., 2010; [1]per crop means kg/ha per growing season.

**Production of quality products**: One globally spread (and perhaps believed) myth by the promoters of organic farming (i.e., avoidance of all chemical inputs including chemical fertilizers) is that organic fertilizers produce better quality products compared to inorganic fertilizers (Mamaril et al., 2009). The reality is that while organic farming may result in better quality products it is not the application of organic fertilizers alone that results in increase of anti-oxidants (e.g., total phenolic content). Scientific evidences show that sustainable use of chemical fertilizers without the use of pesticides can result in high anti-oxidants compared to conventional farming with application of chemical fertilizers. In fact, studies have shown that the polyphenol content (an anti-oxidant) could even be higher in plants applied with inorganic fertilizers for as long as no pesticides are applied (Mamaril, 2004).

**Prices and affordability**: One of the widely spread misconceptions by the advocates of organic fertilizers is that organic materials are cheaper than the inorganic fertilizers. The reality is that inorganic fertilizers are cheaper than organic fertilizers per unit of nutrient content (Mamaril et al., 2009). Inorganic fertilizers have substantially higher nutrient contents, especially N, P, and K, and are also readily available to plants. It can be cost ineffective to transport organic materials with high-moisture and low-nutrient contents (especially FYM and composts) to long distances.

**Nitrogen fixation by legumes**: Leguminous plants can fix atmospheric $N_2$ in the root nodules with help of *Rhizobia*. Amount of N fixed by some common aerobic and anaerobic N-fixing organisms is presented in Table 4, while the nutrient content of some important leguminous plants is presented in Table 3. One of misconceptions about green manures and leguminous crops (e.g., cover crops, legume leaves, twigs, and residues, etc.) is that all their N content is fixed from the atmosphere and all Nis utilized easily by the crops (Mamaril et al., 2009). The reality, however is that the N in green manures and leguminous crops is not necessarily fixed from the atmosphere as a good portion is absorbed from the soil. Also, when green manures or legume residues are incorporated into the soil, not all their N contents are used by the crops as some N is lost during decomposition or mineralization. However, there are exceptions when crops grown in rotation with crops capture nutrient unavailable to crops and recycle the otherwise lost nutrients back to crops. One such case is when crops, weeds, or green manures (grown in rotation with lowland rice) can assimilate nitrate and then recycle the N back to future rice crops through retained biomass. Another case is deep rooting shrubs (such as in agroforestry systems) grown on deep soils, which can capture nutrient from below the rooting depth of crops and recycle them back to future crops (see below details about agroforestry systems).

**Supply of high amounts macro- and micro-nutrients**: One popular is that chemical fertilizers provide only a few macronutrients and not micronutrients (Mamaril et al., 2009). The reality is that while most organic fertilizers contain some micronutrients by nature, there are now several commercially-available inorganic fertilizers containing micronutrients (Table 1). Thus, soils deficient in micronutrients can now be supplied with smaller amount of inorganic fertilizers containing micronutrients rather than large amount of organic materials to supply the same quantity of nutrients required by plants.

**Build-up of soil organic matter**: One popular misconception by advocates of organic fertilizers is that organic materials or organic fertilizers build up SOM irrespective of the amounts they are applied to the soil. Organic materials no doubt supply nutrients and energy for soil organisms that help in accumulating SOM in soils, their contribution to SOM build-up within a short period of time (e.g., one or two years) is widely misperceived or over-exaggerated (Mamaril et al., 2009). The reality is that large quantities of organic materials would be required to build up SOM. Moreover, the amount of SOM formed with addition of organic materials depends on the carbon nitrogen ratio (C:N ratio) of the original materials and conditions during decomposition. To illustrate this, Mamaril et al. (2009) provided a calculation comparing the magnitude of SOM accumulation by rice straw and a hypothetical organic fertilizer. In that calculation, 5 t/ha rice straw (C:N ratio, 10:1; %N in straw, 0.6%) was used, and if no losses of initial straw N during decomposition was considered, then the increase in SOM (C:N ratio, 10:1) in one ha furrow slice soil would only be about 0.023%. However, if 50% of the initial N would be lost through ammonification, nitrification and denitrification, volatilization, or leaching and the remaining 50% taken up by plants, then the SOM build-up would be just 0.011%. Likewise, when an organic fertilizer (e.g., with C:N ratio, 15:1; 8 bags/ha, 50 kg/bag; M.C., 35%) was used, and if no losses of initial N was considered, then the increase in SOM (C:N ratio, 10:1) in one ha furrow slice would also be 0.023%. If 30% N from the organic fertilizer is taken up by rice, 30% N lost by leaching and volatilization, and the remaining 40% N is accumulated in soil as SOM, then %SOM build-up through 8 bags of organic fertilizer would be about 0.0062%. Such magnitudes of increases in SOM due to addition of organic materials (i.e., straw) or organic fertilizers would be far less than what many advocates of organic fertilizers claim. Further, such build-up of SOM occurs only in non-flooded or aerobic soils and not significantly on flooded or anerobic soils where rice is grown (Buresh and Dobermann, 2010).

Similar to organic fertilizer, inorganic fertilizer N, when applied at rates at which maximum yields are achieved, can also result in the build-up of SOM and microbial biomass by promoting plant growth and increasing the amount of litter and root biomass added to soil. Bijay-Singh (2018) reported that only when fertilizer N is applied at rates more than the optimum, it increased the residual inorganic N accelerating the loss of SOM through mineralization. Fertilizer N application can affect SOM in two ways: (i) it may increase SOM by promoting plant growth and increasing the amount of litter and root biomass added to soil compared with the soil not receiving fertilizer N; and (ii) it may accelerate SOM loss through decay or microbial transformation of litter (leaves, straw, manures) and indigenous forms of organic C already present in the soil (Recous et al., 1995).The author also reported that high fertilizer rates can also adversely affect soil microbial biomass.

**Universal application of organic materials**: Advocates of organic fertilizers claim that it is always safe to apply huge amounts of organic materials on every soil, irrespective of the SOM status, including the anaerobic flooded soils. The reality is that excess organic matter could cause zinc and sulfur deficiency especially when the field is continuously flooded (Mamaril, 2004; Ponnamperuma, 1972).In addition, toxicity from products of anaerobic decomposition (such as organic acids and hydrogen sulfide) could also be a concern. Hence, when the SOM in soils is relatively high (>4.0%), organic materials preferably should be applied in dry season or aerobic conditions.

**Contribution of bio-fertilizers***:* Advocates of organic fertilizers claim that microbial or biofertilizers, containing organisms such as bacteria, fungi, algae, actinomycetes, etc., contribute significant amount of nutrients to the crop and can be used in any crop and for all types of ecosystems (Mamaril et al., 2009). The fact is that biofertilizers don't directly contribute nutrients but merely make nutrients available from other sources like atmospheric N or SOM. Soil organisms (bacteria, fungi, algae, actinomycetes, earthworms, etc.) are essential components of the soil, contributing to soil productivity. There are aerobic and anaerobic N-fixing bacteria (e.g., *Rhizobia* fix atmospheric $N_2$ in roots of leguminous pants) and some bacteria and fungi (e.g., *Trichoderma*),which are effective in decomposing or mineralizing SOM, and thus helping farmers to dispose farm wastes and use these to improve soil productivity. Biofertilizers, which are applied to seeds, soils in seedbed, or to composting materials can increase the number of microorganisms and accelerate certain microbial processes such as atmospheric $N_2$ fixation, phosphate solubilization, or cellulose degradation.

While the role of the biofertilizers has been recognised, there are evidences that their effects on crop growth or yield has been inconsistent or not as dramatic as claimed by the advocates of organic fertilizers. Moreover, since most of the microorganisms in biofertilizers work under aerobic conditions, they may not be effective under anaerobic conditions. Conditions where biofertilizers are effective are not defined properly to guide extension workers and farmers. Hence, it is important that the biofertilizers developers indicate the species or strains of organisms present (whether aerobic or anaerobic) and the conditions where the product is effective. Research has shown two important concerns in using organic materials or organic fertilizers. One is that raw organic materials may contain pathogens especially when these are from manures, including human faeces. Another is the level of heavy metals especially when the raw materials are industrial or urban wastes and even household wastes (Mamaril et al., 2009). Hence, bags containing organic materials or organic fertilizers should be properly labelled providing guarantee that these are free of pathogens and that the contents of the heavy metals are within the acceptable levels.

**Possible adverse effects of inorganic fertilizers**: Knowing the drawbacks of inorganic fertilizers makes it easier to mitigate the negative side effects they can cause. In most cases, the benefits of inorganic fertilizers outweigh their disadvantages when they are used correctly. Most problems with inorganic fertilizers occur when they are overused or applied incorrectly. Performing a soil test before planting a crop or before fertilizer application is an accurate way to determine the right type and amount of fertilizer the soil needs. Excessive amount of application of fertilizers has the following plant, soil and environmental consequences: (i) Salt and nutrient accumulation: repeated applications of inorganic fertilizer can lead to the build-up of salt and nutrients in the soil. Salt accumulation in the soil forces plants to expend more energy to draw water from the soil and can cause them to appear wilted or dried out. Soils with an excessive salt concentration have a white crusty surface and can become compacted. Building-up of salt and nutrient toxicity due to heavy application of organic materials is unlikely as long as they are able to fully decompose. In addition, because organic fertilizers are made from natural sources, only limited amounts of fossil fuels are used in production. This means greenhouse gas released into the atmosphere is lower in organic fertilizer production than it is in inorganic fertilizer production; (ii) Runoff: most organic fertilizers are water-soluble and can wash away if there is rainfall shortly after they are applied. Fertilizers that wash away during a heavy rainfall can pollute streams, ponds and other bodies of open water. Storm water runoff laden with inorganic fertilizers can cause algae and other aquatic plants in the water to grow excessively; (iii) Plant damage: incorrectly applied inorganic fertilizers can damage the plants that they are supposed to feed. Fertilizer that comes in contact with the plant leaves can cause leaf scorching if the leaves of the plant are wet; (iv) Leaching: in sandy soils, drainage ditches and other areas where large volumes of water percolate through the soil, inorganic fertilizers can leach away from the root zone of the plant. Inorganic fertilizers that leach into the soil below the plant root systems are wasted since they are inaccessible to plants; and (iv) Application: inorganic fertilizers that are spread over the surface of the soil can cause P and K to build up on the surface of the soil. Nutrients on the surface of the soil are unavailable to the plant roots until they are tilled into the soil; however, disturbing the soil around established plants can damage the root systems. Fertilizers that accumulate on the soil surface can decrease soil pH within the upper 2 to 3 inches of the soil.

**Nutrient requirements from inorganic and organic sources**: Table (5) shows nutrient requirements through chemical fertilizers and organic sources (FYM and crop residues) for various scenarios involving various combinations of inorganic fertilizers and organic materials to achieve target yields of rice, wheat and maize (5, 5 and 10 t/ha, respectively). Rice, wheat and maize are chosen because these are the crops grown predominantly in developing countries across the globe and are highly important from food security point of view in all countries (Timsina and Connor, 2001; Timsina et al., 2010, 2018). Their sustainable production is necessary in all those countries where these are the principal crops. Four scenarios are considered: Scenario 1 is when all nutrients are supplied through 100% chemical fertilizers and with no organic sources; Scenario 2 is when 50% nutrients are applied through chemical fertilizers, and 25% each from FYM and crop residues; Scenario 3 is when 75% nutrients are applied through chemical fertilizers, and 12.5% each from FYM and crop residues; and finally Scenario 4 is when all nutrients are applied through organic sources only (50% each from FYM and crop residues) and with no application of chemical fertilizers. FYM and crop residues are chosen because these are the main sources of organic nutrients in the smallholder crop-livestock or crop-tree-livestock farming systems in tropics and subtropics and also these can contribute to nutrient cycling (Bijay-Singh et al., 2008; Timsina et al., 1991; Thuy et al., 2008; Yadvinder –Singh et al., 2005). In the example, rice residues are applied to wheat and maize crops and maize residues are applied to the rice crop. Nutrient concentrations in fertilizers (urea, TSP and MoP) and organic sources (FYM and crop residues) as reported in Tables 1-3 are considered. Nutrient requirements to obtain 1 t of grain (kg nutrient/t grain) as calculated by QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) model, as widely used in the literature, are presented in Table 6 (Buresh et al., 2010; Chuan et al., 2013; Jansen et al. 1990, Jiang et al., 2017; Setiyano et al., 2010). The model predicts that for rice, wheat and maize, 14.6, 18.0 and 22.3 kg N would be required to obtain 1 t of grain yield, respectively. The respective values are 6.2, 5.9 and 9.2 kg $P_2O_5$ and 19.1, 20.9 and 24.0 $K_2O$ per t grain yield of rice, wheat and maize respectively.

**Table 5. Quantities of chemical fertilizers, FYM and crop residues required (kg/ha) to attain yield targets of rice, wheat and maize (5, 5 and 10 t/ha, respectively) for various scenarios of nutrient application[1].**

| Source | Rice | Wheat | Maize |
|---|---|---|---|
| Scenario 1: 100% through chemical fertilizers (kg/ha) | | | |
| Urea | 159 | 196 | 485 |
| TSP | 68 | 64 | 200 |
| MoP | 159 | 174 | 400 |
| Scenario 2: 50% through chemical fertilizers; 25% each from FYM and crop residues (kg/ha) | | | |
| Urea | 79 | 98 | 242 |
| TSP | 34 | 32 | 100 |
| MoP | 80 | 87 | 200 |
| FYM | 1821 | 2250 | 5575 |
| Crop residues | 1310 | 1263 | 3948 |
| Scenario 3: 75% through chemical fertilizers; 12.5% each from FYM and crop residues (kg/ha) | | | |
| Urea | 119 | 147 | 364 |
| TSP | 51 | 48 | 150 |
| MoP | 119 | 131 | 300 |
| FYM | 913 | 1125 | 2788 |
| Crop residues | 1547 | 1940 | 4806 |
| Scenario 4: 50% each from FYM and crop residues (kg/ha) | | | |
| FYM | 3650 | 4500 | 11150 |
| Crop residues | 6186 | 7759 | 19224 |

[1]Author's calculations.

**Table 6. Nutrient uptake requirements for cereal crops as predicted using QUEFTS[4]**

| Crop | Reciprocal internal efficiency (kg nutrient/1000 kg grain) | | |
|---|---|---|---|
| | N | P | K |
| Rice[1] | 14.6 | 6.2 | 19.1 |
| Maize[2] | 18.0 | 5.9 | 20.9 |
| Wheat[3] | 22.3 | 9.2 | 24.0 |

Source: [1] Buresh et al. (2010); [2]Setiyono et al. (2010); [3]Author's personal communication with IPNI (unpublished) & Chuan et al. (2013); [4]Janssen et al., 1990.

Data in Table 5 reveal that when only chemical fertilizers are used to meet the requirements of high-yielding crops (Scenario 1), only small amounts of fertilizers would be required, and hence the handling, storing, transporting and applying the fertilizers in the fields would not be a big issue. This is in contrast to Scenario 4, where very large amounts of FYM and crop residues would be required to meet crop nutrient requirements and hence the issue of availability as well as all of the above issues would be significantly greater. In Scenario 2 and 3, where some fractions of the amounts are used through organic sources, the issues related to handling, storing, transporting and application of organic materials still be there but much lesser than in Scenario 4. Such extremely large amounts of organic materials as required for Scenario 4, and to the lesser extent for Scenario 2, will not be available, and most countries would need extra lands to increase crop yields if the nutrients are attempted to supply through organic materials only. Extra lands will not be available in any countries due to increase in population. Even if lands would be made available to produce organic inputs, using only organic sources will be highly laborious, costly, and impractical. Further, nutrient contents in organic materials are highly variable and they release nutrients slowly and at variable rates. Information on period of nutrient release and on the rates by which nutrients are mineralized for the plants to absorb are not provided to farmers, leading to uncertainties in calculations of nutrients to be supplied through such sources.

Under the current farming situation of most of the smallholders in the developing countries, only a small amounts of organic materials are available, and hence farmers apply only a small proportion of organic materials to their crops, or vegetables or fruits. Innovative and novel techniques or methods would be required to produce on-farm organic materials to supply larger proportion of nutrients through them. This is discussed in the next section.

**Organic materials from crop-tree-livestock integration**: The calculations presented in previous section reveal that organic fertilizers or organic materials obtained from conventional crop or crop-livestock system are not enough to meet crop nutrient demand for high yields and achieve food security. Novel methods and approaches would be required to increase biomass for supplying adequate amounts of nutrients for high yield and achieve food security. One of such approaches is crop-tree-livestock integration, also called agroforestry system, in which farmers can grow crops and trees in right proportions as in the intercropping system so that crop residues and tree leaves can provide enough nutrients to build and maintain soil fertility, supply nutrients to plants and also can provide green fodder to livestock. Evergreen Agriculture, an advanced form of agroforestry system, is a novel approach of maintaining soil fertility and providing nutrients to plants and fodder to livestock, and is now practiced in several African countries and also in some countries in South Asia and South America (Garrity, 2004; Garrity et al., 2010). Evergreen Agriculture is defined as the integration of trees into annual food crop systems, using both perennial and annual species (trees, food and vegetable crops), resulting in maintenance of a green cover on the land throughout the year. Depending upon which woody species are used and how they are managed, their incorporation into crop fields and agricultural landscapes can maintain vegetative soil cover all year-round, bolster nutrient supply through $N_2$ fixation and nutrient cycling, enhance suppression of insect pests and weeds, improve soil structure and water infiltration, produce greater amount of food, fodder, fuel, fiber and income directly from products produced by the intercropped trees. More importantly, this can enhance carbon storage both above- and below-ground, produce greater quantities of organic matter in soil surface residues, result in more effective conservation of above- and below-ground biodiversity, sequester carbon in trees and soil, and thus can mitigate emissions and tackle climate change (Garrity, 2004; Garrity et al., 2010).The overall benefits expected of an evergreen farming system are increased food crop yields and/or overall profitability, lower costs of production, and healthier soils (Garrity, 2004). Evergreen Agriculture contributes to integrated soil fertility management, and the knowledge to adapt these to local conditions that maximize chemical fertilizer and organic resource use efficiency and crop productivity. It is also compatible with reduced tillage, increased residue retention on the soil surface, and other principles of CA in situations where these are feasible and appropriate (Gathala et al., 2015, 2016). Evergreen Agriculture also broadens the principle of crop rotations to encompass the role of fertilizer trees (e.g., *Faidherbia albida*) and/or other cash crop trees to enhance soil fertility more effectively and provide needed biological and income diversity in the farm system (Garrity, 2004; Garrity et al., 2010).In this respect, the types of intercropped trees may include species whose primary purpose is to provide products or benefits other than soil fertility replenishment alone, such as fodder, fruits, timber, and fuel wood. In such cases, the trees are expected to provide an overall value greater than that of the annual crop within the area that they occupy per unit area in the field.

The principles of Evergreen Agriculture have already been widely applied across several countries in Africa where they have been adapted in a diversity of situations, often building successfully on proven indigenous farming technologies and where complexity is a common feature of the agricultural systems (Garritty et al., 2010). For example, in Zambia and Niger, Evergreen Agriculture is practised with conservation farming with *Faidherbia albida*, which is a N-fixing acacia species that is indigenous to Africa and is widespread throughout the continent. What makes it unique is its growth habit, known as 'reverse leaf phenology' (Akinifessi et al., 2010; Barnes and Fagg, 2003). *Faidherbia* goes dormant and sheds its foliage during the early rainy season, at the time when field crops are being established, thus exhibiting minimal competition while enhancing yields and soil health. Its leaves only regrow at the end of the wet season. This unusual phenology makes it highly compatible with food crops, since it does not compete with them significantly for light, nutrients or water during the growing season. In contrast, annual crops in the vicinity of *Faidherbia* trees tend to exhibit improved performance and yield (Akinifessi et al., 2010; Barnes and Fagg, 2003).

An important question in soil fertility management by reducing the use of chemical fertilizers is how the biomass production can be increased to enhance surface cover and to generate greater quantities of organic nutrients to complement whatever amounts of inorganic fertilizers a smallholder farmer can afford to apply. Across Africa, practical systems for intercropping fertilizer trees in farming systems have been developed and are now being extended to hundreds of thousands of farmers across the continent (Garrity et al., 2010). The portfolio of options includes intercropping maize with *Gliricidia sepium*, *Tephrosia candida* or pigeon peas, or using trees such as *Sesbania sesban* (Akiniffesi et al., 2010). One particularly promising system in Africa is the integration of the *Faidherbia albida* into crop fields at a 10 m by 10 m spacing. Research has revealed that several tons of additional biomass/ha can be generated annually to accelerate soil fertility replenishment and provide additional livestock fodder, and that there were dramatic increases in maize yield when it was grown in association with *Faidherbia* depending on the age and density of trees, agronomic practices used, and the weather conditions (Barnes and Fagg 2003; Kang and Akinifessi, 2000). Further, *Faidherbia's* effects tended to be most remarkable in conditions of low soil fertility. Akinifessi et al. (2010) concluded that fertilizer trees such as *Faidherbia*, *Gliricidia*, and *Leucaena* can add 34-300 kg N/ha/year through BNF (Table 4), and that, depending on crops, nutrient contributions from fertilizer tree biomass can reduce the mineral N requirement by upto 75%. Further, research in Africa has demonstrated that integrating fertilizer trees and shrubs into CA can dramatically enhance both fodder production and soil fertility (Garrity et al., 2010). This broadens the concept of crop rotations to incorporate the role of fertilizer/fodder trees to more effectively enhance soil fertility and provide needed organic materials for increasing crop yield, increase income and achieve food security. Such novel approaches can help for a gradual shift of government investments from fertilizer subsidies to sustainable on-farm fertility regeneration.

## CONCLUSION AND RESEARCH NEEDS

Fertilizers, when applied at rates less than the optimum at which maximum yields are obtained, stimulate crop growth, leading to increasing crop residue inputs to the soil and, in turn, increasing the rate of SOM. The balanced application of N, P, and K fertilizers results in further significant improvement in the soil health in terms of increased SOC and soil microbial biomass. As a decline in SOM following the application of fertilizer is not a general phenomenon, a spiral of decline in soil functioning and crop productivity due to fertilizer use is not expected. However, application of fertilizers more than the optimum level not only adversely influences biological communities in the soil but may also result in increased residual inorganic N, which can enhance SOC mineralization and loss of SOC. Because there exists large spatial and temporal variability in soil N supply, crop response to N fertilization is site-specific. Thus, site-specific nutrient management strategies based on principles of synchronization of crop demand of nutrients with supply from all sources including soil and fertilizer hold great potential for ensuring high yields of crops along with maintenance or improvement in soil health (Buresh et al., 2010; Timsina et al., 2010).

Agronomic and soils research, including agroforestry systems, reviewed and analysed in this paper demonstrates that sustainable intensification through integrated management of inorganic and organic nutrients is crucial for sustainable soil fertility management and to achieve food security. The extent to which fertilizers can contribute to economic and efficient crop production, and concomitantly benefit the soil in terms of quality or health, is dictated by the adoption of management practices that ensure that fertilizers are not applied indiscriminately to agricultural crops. Fertilizers should never be applied in amounts greater than what is required to obtain optimum or high yields. Ideally, fertilizers should be managed on a site-specific basis, whether based on the nutrient status of soil or plants in a given field, so that they are applied in the right amount and at a right time according to the needs of the soil-plant system. The application of fertilizers in a balanced proportion with other nutrients and integrated nutrient management based on organic and inorganic sources can lead to further improvements in soil health and soil fertility and productivity. There is a need to document the effects of different chemical fertilizers on the stability of SOM and the long-term fate of organic materials in different cropping systems.

Finally, the review also reveals that organic sources are not as effective during the wet season or under anaerobic conditions as compared to that in dry season or aerobic conditions. In dry season, mineralization of organic N is slower than in wet season, suggesting that organic materials should preferably be applied during the dry season and in aerobic conditions. Based on the available scientific evidences, the most practical strategy would be the application of the combination of organic and inorganic materials at a ratio of 25:75 to obtain yields comparable to that from inorganic N alone for crops grown in dry season or under aerobic conditions. However, even for this suggested amount, it depends on the type, quality and nutrient content, and the availability and practicality of application of organic fertilizers. Benefits of inorganic fertilizers when applied in appropriate amounts and doses under specific soils (including aerobic and anaerobic) and environmental conditions have been well documented, but not enough documented information is available for organic materials or organic fertilizers. Hence, proper field experiments across the country must be conducted to determine the soils and environmental conditions where the organic fertilizers including biofertilizers can be effective to better guide and benefit farmers before promoting or spreading the use of organic fertilizers. Finally, crop-tree-livestock integration or an agroforestry system would be the most effective strategy to maintain soil fertility, supply larger proportion of nutrients to crops, and provide fodder to livestock. A new concept of Evergreen Agriculture has now been widely adapted by farmers across several countries in Africa. Such a novel approach should be introduced and promoted in areas of South Asia, Including Nepal. In many areas in Nepal, especially in hills and mountainous regions, there exist several species and types of annual and perennial trees in homesteads, farmlands and forests (Timsina et al., 1991), and Evergreen Agriculture seems to be a sustainable strategy to improve on-farm soil fertility, increase crop yields, provide fodder to livestock, and achieve food security. In areas where trees are sparse, government policies should aim to increase tree plantation and promote Evergreen Agriculture. This will encourage farmers to plant trees and ultimately promote the use of organic materials/fertilizers for sustainable soil fertility management and achieve food security.

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