agronomy

Review

Can Organic Sources of Nutrients Increase Crop Yields to Meet Global Food Demand?

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Abstract: Meeting global demand of safe and healthy food for the ever-increasing population now and into the future is currently a crucial challenge. Increasing crop production by preserving environment and mitigating climate change should thus be the main goal of today's agriculture. Conventional farming is characterized by use of high-yielding varieties, irrigation water, chemical fertilizers and synthetic pesticides to increase yields. However, due to either over- or misuse of chemical fertilizers or pesticides in many agro-ecosystems, such farming is often blamed for land degradation and environmental pollution and for adversely affecting the health of humans, plants, animals and aquatic ecosystems. Of all inputs required for increased agricultural production, nutrients are considered to be the most important ones. Organic farming, with use of organic sources of nutrients, is proposed as a sustainable strategy for producing safe, healthy and cheaper food and for restoring soil fertility and mitigating climate change. However, there are several myths and controversies surrounding the use of organic versus inorganic sources of nutrients. The objectives of this paper are: (i) to clarify some of the myths or misconceptions about organic versus inorganic sources of nutrients and (ii) to propose alternative solutions to increase on-farm biomass production for use as organic inputs for improving soil fertility and increasing crop yields. Common myths identified by this review include that organic materials/fertilizers can: (i) supply all required macro- and micro-nutrients for plants; (ii) improve physical, chemical and microbiological properties of soils; (iii) be applied universally on all soils; (iv) always produce quality products; (v) be cheaper and affordable; and (vi) build-up of large amount of soil organic matter. Other related myths are: "legumes can use entire amount of N_2 fixed from atmosphere" and "bio-fertilizers increase nutrient content of soil." Common myths regarding chemical fertilizers are that they: (i) are not easily available and affordable, (ii) degrade land, (iii) pollute environment and (iv) adversely affect health of humans, animals and agro-ecosystems. The review reveals that, except in some cases where higher yields (and higher profits) can be found from organic farming, their yields are generally 20–50% lower than that from conventional farming. The paper demonstrates that considering the current organic sources of nutrients in the developing countries, organic nutrients alone are not enough to increase crop yields to meet global food demand and that nutrients from inorganic and organic sources should preferably be applied at 75:25 ratio. The review identifies a new and alternative concept of Evergreen Agriculture (an extension of Agroforestry System), which has potential to supply organic nutrients in much higher amounts, improve on-farm soil fertility and meet nutrient demand of high-yielding crops, sequester carbon and mitigate greenhouse gas emissions, provide fodder for livestock and fuelwood for farmers and has potential to meet global food demand. Evergreen Agriculture has been widely adapted by tens of millions of farmers in several African countries and the review proposes for evaluation and scaling-up of such technology in Asian and Latin American countries too.

Keywords: organic farming; conventional farming; organic nutrients; chemical fertilizers; global food demand; agroforestry system; evergreen agriculture

1. Introduction

Providing enough, safe and healthy food to their citizens by avoiding environmental degradation under current and the projected climate change are the most important issues that all countries are facing in the world. Global food production increased by 70% from 1970 to 1995 in developing countries, largely due to the green revolution technologies (also called conventional agriculture) which uses high-yielding inputs such as improved and high-yielding varieties (HYVs), irrigation, chemical fertilizers and synthetic pesticides [1,2] and the production has been increasing after that period too. As per FAO's revised projection, global food production should be 60% higher in 2050 than in 2005/2007 to feed the projected global population of 10 billion [3,4]. To close this gap, total crop production needs to be increased even more from 2006 to 2050 than it did in the same number of years from 1962 to 2006 [5]. Though in the past green revolution technologies have increased crop yields and produced food to meet caloric requirements of the global population [6], there are also increasing concerns about the environmental costs, such as increased soil erosion, surface and groundwater contamination, greenhouse gas emissions, increased pest resistance and reduced biodiversity and so forth, with use of such technologies [7,8]. These concerns suggest that more sustainable methods of food production are essential to meet the food requirements of ever-increasing population now and into the future but at the same time such methods must maintain natural resource base by avoiding land degradation and mitigating climate change. The challenge now is to fine-tune the existing technologies or develop alternative technologies that can increase crop yields to meet global food demand of increasing population but without compromising with the natural resources or the environment.

Over the past 2–3 decades organic agriculture has been advocated as an alternative form of farming to produce food sustainably by reducing the impact of agriculture on the environment [9–12]. All these authors believe that a widespread shift from conventional to organic farming could feed the world with safe and healthy food now and into the future and also could avoid environmental degradation. Their claims however have been widely criticized by many authors [13–18], as they all argue that organic farming without the use of synthetic fertilizers, pesticides, or genetically-engineered crops simply cannot feed the projected 10 billion people for 2050 and that extra lands and water would be required for organic farming to produce similar amount of food to that from conventional farming. Kirchmann et al. [2,19,20] warned that expansion of areas for organic farming into forests or natural lands to feed the projected global population would lead to loss of biodiversity or natural habitats, increase of greenhouse gas emissions and depletion of ecosystem services. Ammann [21] and Ronald and Adamchak [22] however proposed a mid-way or a balanced view suggesting that a combination of high technology and organic techniques (i.e., a hybrid of organic and conventional farming) may provide more realistic and sustainable solutions.

Although many production factors (nutrients, water, pest and diseases, labour, prices of inputs and outputs, etc.) contribute to crop yield, it seems from various debates and arguments surrounding the use of conventional and organic farming that availability of required amounts of plant nutrients and the practicality of their use to produce enough food to feed 10 billion people remain the central issues of all these debates. While role of nutrients, whether organic or inorganic, for increased crop production is universally and unequivocally recognised, there seem to be several myths or misconceptions of using organic farming and/or organic sources of nutrients. Some sectors of the society, particularly those activists or advocates influenced by International Non-governmental Organizations (INGOs) or Non-governmental Organizations (NGOs), some researchers and extensions workers and even the government policy makers in many developing countries claim that use of the chemical fertilizers adversely affects soil quality and decreases the soil and crop productivity, whereas the use of organic farming or organic nutrients unquestionably and universally increases soil and crop productivity. These claims however have very little scientific basis and any decline in soil or crop productivity due to the use of chemical fertilizers could be due to their either over- or misuse.

This paper focuses on the discussion on nutrient sources for crops grown under organic and conventional farming and tries to argue whether existing sources of organic materials can supply enough nutrients to increase crop yields so as to meet the food demand of the growing population. The specific objectives are: (i) to clarify some of the myths or misconceptions regarding organic nutrients/fertilizers and chemical fertilizers 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 on-farm soil fertility and increasing crop yields. Such clarifications and alternative solutions could help planners and policy makers of any country to develop policies and programs to promote for the rationale use of inorganic and/or organic nutrient inputs to achieve food security and get rid of poverty. The paper is organised into the following sections: (i) Differences between organic and conventional agriculture (iii) Sources of inorganic and organic nutrients for crops (ii) Myths and realities of use of organic materials/fertilizers and chemical fertilizers (iii) Nutrient requirements and supply for organically- and conventionally-grown crops (iv) Need for site-specific nutrient management (v) Alternative approaches to increase on-farm soil fertility and nutrient supply (vi) Conclusions and research and policy implications.

2. Organic Agriculture: Concepts, Principles and Global Performance against Conventional Agriculture

FAO has defined organic agriculture as a holistic production management system which promotes and enhances agro-ecosystem health, including biodiversity, biological cycles and soil biological activity. It emphasizes the use of management practices in preference to the use of off-farm inputs, considering that regional conditions require locally adapted systems (http://www.fao.org/docrep/meeting/x0075e.html). This is accomplished by using, where possible, agronomic, biological and mechanical methods, as opposed to using synthetic materials, to fulfil any specific function within the system. International Federation of Organic Agriculture Movement (IFOAM) has defined organic agriculture as a production system that sustains the health of soils, ecosystems and people and relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of external inputs with adverse effects and such agriculture combines tradition, innovation and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved [23]. IFOAM stresses that organic agriculture is based on the principles of health, ecology, fairness and care. It can sustain and enhance the health of soil, plant, animal, human and planet; sustain living ecological systems and cycles; build on relationships that ensure fairness about the common environment and life opportunities; and manage in a precautionary and responsible manner to protect the health and well-being of current and future generations and the environment. National Research Council (NRC) from USA [24] has also identified organic methods as one of several innovative systems that can meet production, environmental and socio-economic objectives and sustainability goals. Despite the heavy emphasis on, and importance given to organic agriculture by various national and international entities it is now practised only on about 50.9 Mha (1.1% of total agricultural land) by 2.4 million farmers globally, with about 87 countries having some sort of organic regulations or certifications [25].

Organic farming 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 synthetic pesticides and genetically-engineered crops. Organic agriculture uses organic materials to supply nutrients and to control pests and diseases. There are contrasting results from both developed and developing countries regarding the performance of organic versus conventional agriculture. In one of the earliest reviews, Stanhill [26], using data from developed countries and mostly from prior to 1985, reported 9% lower yield for organic crops compared to conventional ones. Penning de Vries et al. [27], based on results from a crop simulation model, concluded that organic agriculture can only produce enough food to feed 9 billion people assuming moderate amounts of diet and with animal proteins. Lotter [28] reported that large scale conversion from conventional to organic agriculture is possible only if meat consumption is reduced. Subsequently, Badgley et al. [9], comparing yield data between organic and conventional agriculture from 293 studies reported about 8% lower yield for organic agriculture. Kirchmann et al. [19,20], however reported that organic crop yields are 25–50% lower than conventional ones, which were mainly attributed to lower nutrient availability, poorer weed control and limited possibility to improve the soil nutrient status.

Ponti et al. [29], using a meta-dataset of 362 studies globally, concluded that individual yields of organic crops, on an average, were 20% lower than conventional crops. In their study, the organic yield gaps varied significantly between crop groups and regions and the gaps increased as yields of conventional crops increased. The results of Ponti et al. however are not surprising because potential yield of any crop is climate-derived and not limited by water or nutrients, with pests and diseases fully controlled [30]. Yield potential of any crop can be increased with increasing amounts of nutrients and water and by fully controlling weeds, pests and diseases so that crop will not be stressed by any biotic and abiotic factors [30–32]. On the other hand, even the well-managed organic crops generally do not receive adequate amounts of nutrients and pests and diseases are not fully controlled. Also from a meta-analysis of 316 yield comparisons in 66 studies, Seufert et al. [12] concluded that organic crops in developed countries yielded 20% lower but when developed and developing countries were combined, they yielded 25% lower than their conventional counterparts. However, they also found that for certain crops and for certain growing conditions and management practices, yields of organic crops matched their conventional counterparts. Results from Badgely et al. [9], Ponti et al. [29] and Seufert et al. [12] suggest that adoption of organic agriculture under conditions in which it performs well might close the yield gap between organic and conventional crops.

The results and conclusions of these three studies [9,12,29] were heavily disputed by Cassman [33], Connor [16], Goulding et al. [15] and Dobermann [34], who all argued that their yield data and assumptions made on nutrient availability from organic sources were quite unrealistic. Connor [16] and Dobermann [34] questioned about the analysis methods of Badgely et al. owing to their reliance on yield ratios as in many cases they represented large differences in crop management. Due to flaws and criteria for design and evaluation of comparisons between organic and conventional agriculture, Kirchmann et al. [2] proposed three stringency criteria to ensure scientific quality of data: requirements of similar initial soil fertility, comparable crop production type and quantification of off-farm organic nutrient inputs. Based on the review of above studies, crop yields from organic farming are generally about 20–50% lower although in some cases their yields and economic returns are higher than from conventional farming.

3. Sources of Organic Nutrients

Several terms (e.g., organic farming, natural farming, alternative farming, regenerative farming, low-input agriculture, sustainable agriculture, etc.) are used in literature, sometime interchangeably, to describe organic farming. Likewise, many other terms (e.g., organic materials, organic fertilizers, organic nutrients and bio-fertilizers, etc.) are used to describe sources of nutrients. Crop plants require nutrients derived from organic as well as inorganic sources. Common inorganic sources of nutrients include fossil-fuel derived chemical fertilizers while organic sources include decomposed or undecomposed plant and animal materials. Many different types of chemical fertilizers in various formulations are available in markets in all countries. Chemical fertilizers, especially the nitrogenous fertilizers, are prone to losses from soil-plant systems. Hence, smart and innovative fertilizers such as controlled-release or slow-release fertilizers (e.g., poly-coated urea), deep placement (e.g., urea super granules), or nitrification inhibitors are being developed and used to reduce losses and increase the efficiency of fertilizers [35]. Precision nutrient management such as site-specific nutrient management (SSNM) can help reduce and/or optimize the fertilizer use considering the field, soil or site history and characteristics and resulting nutrient needs. This will be discussed in Section 6.

Some of the organic materials used as organic sources of fertilizers in Asia 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, biogas slurry, oilcakes and so forth, (ii) biodegradable wastes, including kitchen and market wastes, fruits and vegetables peelings and biosolids and so forth, (iii) farmyard manure (FYM) and litters such as cattle manure, poultry manure, composts, vermicomposts and so forth, from on-farm and off-farm sources and (iv) forest and grasslands wastes, such as tree leaves, branches and twigs, shrubs and herbs underneath trees, roadside and community grasses and weeds and so forth. Other common sources of organic nutrients include growing food and non-food legumes as intercrops or rotational crops for current or residual N contribution, surface or residue recycling and in situ or ex-situ N_2-fixing green manure crops and so forth [36,37]. Organic fertilizers 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 (for example, granules made from cattle or poultry manure) developed from processing of organic materials. Finally, bio-fertilizers 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 [36].

In recent years, many kinds and formulations of organic fertilizers and bio-fertilizers are produced in many countries in South and SE Asia as well as imported from other countries and are floated in the markets as organic fertilizers. Some of such fertilizers, for example in Nepal, are bio-organic fertilizers, *Jaibik* Superphosphate (P), *Jaibik dhulo* (N), *Jhol mal*, HB 101, Bonsoon Super *Prangarik Mal*, Green Gold Super *Prangarik Mal* (Nepal), Chao Nang granules, Super Green plus, Super Green plant, Super Green mix and Premium Azosp, Premium Phospofix and Premium Azotoplus (India) [38]. Likewise, some common organic fertilizers in the Philippines are coco-composts, vermicomposts, Kalikasan Organic, Norfarco Bioorganic, Bio-green Compost, Foundation LCF Organic, Green Harvest Organic, Bio-earth Organic and so forth [36].

4. Organic versus Inorganic Materials/Fertilizers: Myths and Realities

Organic materials are widely used, albeit in small quantities, especially in subsistence farming systems in Asia, Africa and Latin America. Organic materials can improve soil's physical properties such as structure and aggregation and water holding capacity and drainage, biological properties such as increased microbial populations for biological activity and chemical properties such as nutrient holding capacity through increased cation exchange capacity and increased ability to resist changes in soil pH [39]. Improvement in soil physical properties can improve the medium for plant growth especially under well-drained, aerobic condition but less so under submerged paddy field soils, which during land preparation are typically puddled resulting in the breakdown of soil structure [40]. Submergence or flooding tends to buffer pH near neutrality and reduces the decomposition of native soil organic matter (SOM) or mineralization of soil organic nitrogen (SON) as compared to aerobic soils. In addition, 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 [40]. Organic materials can also stimulate the activity of aerobic bacteria found in well-drained soils and, to some extent that of anaerobic bacteria found in submerged soils [36].

There are several myths about organic materials/fertilizers and inorganic fertilizers [36,41]. Many of the myths, however, seem to be mostly based on guesses, perceptions, or prejudices, or for political motives, without enough scientific evidences. Some of such myths and associated facts are discussed below:

4.1. Chemical Fertilizers Deteriorate Soil Physical Properties and Degrade Lands

A common myth among the advocates of organic farming is that the chemical fertilizers destroy the soil physical and chemical properties while organic materials or organic fertilizers improve the soil structure and water holding capacity of all soils [36]. Chemical fertilizers are also blamed for soil deterioration through alteration of soil physical properties and making soils acidic [37]. Some policy makers, politicians and even researchers and extension workers perceive that inorganic fertilizers, whether applied in small or large quantities, can degrade soils (structural change and acidification, etc.) and decline soil or crop productivity. There are, however, no scientific evidences demonstrating that the chemical fertilizers, when applied in optimum rates for high yield, destroy soil structure or reduce soil water holding capacity. The reality is that chemical fertilizers per se do not deteriorate soils by changing soil texture or making them 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 applied in excessive amounts they may change soil texture, acidify soil and reduce microbial communities. In most subsistence farming systems practiced in Asia, Africa and Latin America, the use of chemical fertilizers is too low and thus above issues might not be quite important.

Although organic materials, when used as soil cover or mulch, can improve the soil physical properties, such benefits are mostly limited to aerobic soils through improved water retention, reduced soil crusting, increased soil porosity and reduced erosion. In contrast, flooded rice fields are puddled during land preparation destroying the soil structure and hence improvements of soil physical properties are of little significance to such fields. Improvements in soil physical properties however 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 [42,43]. In CA, soil is tilled to a minimum extent and crop residues are retained in the soil to help build up of SOM [43,44].

4.2. Organic Materials Are Available in Adequate Amounts and Have High Nutrient Contents

Advocates of organic fertilizers generally claim that there is enormous amount of organic materials (manures, crop residues, green manures, bio fertilizers, etc.) which contain high amount of essential nutrients to supply the amounts as per the crop demand for high yield. The reality, however, is that organic materials are not universally available in large quantities and contain very minimal macro- and micro-nutrients compared to inorganic fertilizers (Tables 1 and 2).

Table 1. Nutrient contents (%) of some commonly used organic materials in South and SE Asia (adapted from BARC, 2012 and Timsina, 2018, with permission from BARC, Bangladesh, 2012 and Agriculture & Forestry University, Nepal, 2018).

Organic Materials	Nutrient Content (%)			
	N	P_2O_5	K_2O	S
Cow dung (Fresh 60% MC *)	0.50	0.34	0.6	-
Cow dung (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	-

Source: [41,45]; * MC = Moisture content; - indicates data not available.

Table 2. Nutrient contents (%) of some commonly used green manure crops and crop residues in South and SE Asia (adapted from BARC, 2012 and Timsina, 2018, with permission from BARC, Bangladesh, 2012 and Agriculture & Forestry University, Nepal, 2018).

Green Manure Crops/ Crop Residues	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	*Vigna mungo*	70	0.80	0.46	1.15	0.30
Cowpea	*Vigna unguiculata*	70	0.70	0.34	1.15	-
Pea	*Pisum sativum*	-	1.97	-	-	-
Sun hemp	*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	*Zea mays*	15.5	0.59	0.71	3.00	-
Sugarcane leaves	*Saccharum officinarum*	20	1.00	1.15	3.21	-
Rice hull	*Oryza sativa*	15	0.31	0.16	0.85	-
Coconut husk	*Cocos nucefera*	-	1.75	0.27	2.06	-
Banana stem	*Musa* sp.	-	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	-

Source: [41,45]. – indicates data not available.

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/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 nutrient value of manures. These factors can vary seasonally on and among farms and regionally or on a larger geographic scale. Thus, if different nutrients required for high yields are to be supplied solely through the organic sources, excessively large amounts and volumes of organic materials would be required (Table 3). The exception is that organic materials, especially crop residues (e.g., rice residues), can supply (recycle) considerable potassium (K), sometime even more than crop needs [46,47].

There is poor synchronicity between crop demand and N release from organic manures as N from organic sources could be released during periods without a crop and thus such N could be exposed to leaching when precipitation occurs. Bergstrom and Kirchmann [48,49] demonstrated through two lysimeter studies that leaching of N through NH_4NO_3 was lower compared with animal manures or green manures. Likewise, Aronsson et al. [50] and Torstensson et al. [51] also demonstrated from long-term field studies in Sweden that N losses through leaching were higher in organic than in conventional systems. These results demonstrate that organic N sources are more vulnerable to leaching than inorganic fertilizers because N from organic sources maybe released during periods when there is no crop uptake of N.

Table 3. Quantities of chemical fertilizers, farmyard manure (FYM) and crop residues required (kg ha^{-1}) to attain yield targets of rice, wheat and maize (5, 5 and 10 t ha^{-1}, respectively) for various scenarios of nutrient application (adapted from Timsina, 2018, Agriculture & Forestry University, Nepal, 2018).

Source	Rice	Wheat	Maize
Scenario 1: 100% through chemical fertilizers (kg ha^{-1})			
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^{-1})			
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^{-1})			
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^{-1})			
FYM	3650	4500	11150
Crop residues	6186	7759	19224

[1] Author's calculations; Source: [41].

4.3. *Organic Fertilizers Undoubtedly Can Produce Quality Products*

Promoters of organic farming commonly claim that organic farming or organic fertilizers produce better quality products compared to conventional farming or chemical fertilizers [36]. In fact, a review of multiple studies shows that organic varieties do provide significantly greater levels of vitamin C, iron, magnesium and phosphorus than non-organic varieties of the same foods [52]. Crinnion [53] also reported that organic varieties, while being higher in all these nutrients, are also significantly lower in nitrates and pesticide residues. Meta-analyses based on 343 peer-reviewed publications also indicated that the concentrations of a range of antioxidants were substantially higher in organic crops/crop-based foods than non-organic ones, with higher percentage of phenolic acids, flavanones, stilbenes, flavones, flavanols and anthocyanins [54]. There is also consistent evidence that, in general, organic plant-based foods contain a higher amount of beneficial, health-promoting secondary plant compounds than non-organic plant-based foods. For example, tomatoes grown on fields that have been organically managed for 10 years exhibited respectively 79 and 97% higher quercetin and kaempferol aglycones (i.e., the flavonoid concentrations) than their conventional counterparts [55]. Likewise, a long-term biannual rotation with cauliflower coupled with legume cover crop in an organic system optimized the nutrient fluxes of globe artichoke, suggesting as the most promising approach to foster long-term sustainability for the Mediterranean climate [56]. In a follow-up study in the same environment, polyphenol and Fe and K contents and dihydroxycinnamic and dicaffeoylquinic acids of globe artichoke were higher in organic system than in conventional system [57]. Willer et al. [23] also reported that organically processed products do not contain hydrogenated fats and other additives whose negative health impacts are widely acknowledged. Organic foods are more potent suppressors of the mutagenic action of toxic compounds and inhibit the proliferation of certain cancer cell lines. Clear health benefits from consuming organic dairy products have also been demonstrated regarding allergic dermatitis [53]. Finally, Parrott and Marsden [58] reported an improvement in taste and nutritional content of products by the farmers converted into organic system. Due to high quality of organic products, farmers practicing organic farming can receive higher economic returns due to higher premiums of the products.

While many studies such as above show increase in anti-oxidants and polyphenolics in organically-grown crops or foods, there are also evidences that it is not the application of organic farming alone that results in increase of anti-oxidants, it is when sustainable use of chemical fertilizers but without the use of chemical pesticides can also result in high anti-oxidants.

In fact, some studies have shown that the polyphenol content could be even higher in plants applied with inorganic fertilizers for as long as no pesticides are applied [37]. In the most extreme case, Miller [18] argued that organic foods are less healthy because of the presence of fungi, bacteria and animal manure and provided several examples of organic foods that had dangerous amounts of these substances on them. Thus, it seems unclear from these studies regarding the superiority of organic products over the non-organic ones. More research would be required comparing the performance of organic versus conventional farming or organic versus inorganic fertilizers as the benefits of organic farming/nutrients in terms of product quality or presence of antioxidants is not yet universally accepted. Further, 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 [36]. 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.

4.4. Organic Fertilizers Are Cheaper and Affordable

One of the widely spread misconceptions by the advocates of organic fertilizers is that organic sources of nutrients are cheaper than the inorganic fertilizers. Research has however shown that, on per unit of nutrient content basis, inorganic fertilizers are cheaper than the organic fertilizers [36]. Inorganic fertilizers contain substantially higher amounts of nutrients, especially macro-nutrients than organic manures. Nutrients from chemical fertilizers are also readily available to plants than that from organic sources. Thus, compared to chemical fertilizers, it can be cost ineffective to purchase, transport and apply organic materials such as FYM and composts with high-moisture and low-nutrient contents.

4.5. Legumes Can Use All N_2 Fixed from Atmosphere

Leguminous plants can fix atmospheric N_2 in the root nodules with the help of aerobic and anaerobic N_2-fixing organisms (Table 4). One of the common misconceptions about green manures, leguminous crops and cover crops and residues and so forth is that all their N content is fixed from the atmosphere and all N is utilized easily by the crops [36]. 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 details about agroforestry systems in a later section below).

Table 4. Amount of N_2 fixed (kg ha^{-1}) by some common aerobic and anaerobic N_2-fixing organisms and tree legumes (adapted from Akinnifesi et al., 2010, Canadian Center of Science and Education, 2010).

Group	N_2-Fixing Organisms/Legumes	Amount of N_2 Fixed (kg ha^{-1})
Aerobic	*Azospirillium* sp.	20–40 $season^{-1}$
	Klebsiella	32 $year^{-1}$
	Anabaena (Cyanobacter/Blue green algae)	15–45 $crop^{-1}$
	Nostoc (Cyanobacter/Blue green algae)	15–45 $crop^{-1}$
	Enterobacter	32 $year^{-1}$
	Achromobacter	32 $year^{-1}$
	Klebsiella	32 $year^{-1}$
	Cyanobacteria/Blue green algae	15–45 $crop^{-1}$
Tree and perennial legumes	*Gliricidia sepium*	212 $year^{-1}$
	Acacia anguistissima	122 $year^{-1}$
	Leucaena collinsi	300 $year^{-1}$
	Cajanus cajan	34–85 $crop^{-1}$
	Sesbania sesban	84 $season^{-1}$

Source: [59].

Even though legumes or cover crops can fix N_2 from atmosphere they use lands for them to grow at the cost of cropping of main staple crops. In developed countries where mostly monoculture is practiced, inclusion of legumes as a second crop may not be a great issue but in developing countries with small holder farming systems, double or multiple cropping with 200–300% annual cropping intensity is a common phenomenon. For example, rice-wheat or rice-maize systems are practiced often as double cropping and on many occasions by including a third crop in large areas of South and SE Asia [35,60]. Meeting food security of their people through staple crops (rice, wheat, maize, etc.) is high priority of the governments. Thus, they cannot sacrifice their lands to grow non-staple crops such as legumes instead of staple ones unless replacement of the latter by the former is economically viable without much reduction in total system productivity. Even for the developed countries, there are not enough N_2-fixing cover or legume crops that could fertilize all their crops. Many studies have overestimated the contribution of biological nitrogen fixation (BNF) by legumes. One of such studies is that of Badgley et al. [9] who grossly overestimated the global N supply through BNF, which was immediately disputed by Connor [16] and Dobermann [34].

4.6. Chemical Fertilizers Cannot Supply Micro-Nutrients

One popular misconception about chemical fertilizers is that they provide only a few macro-nutrients and not micro-nutrients. The reality is that while most organic fertilizers contain some micro-nutrients by nature, there are now several commercially-available inorganic fertilizers containing micro-nutrients [36]. Thus, soils deficient in micro-nutrients can now be supplied with smaller amount of inorganic fertilizers containing micro-nutrients rather than large amount of organic materials to supply the same quantity of micro-nutrients required by plants.

4.7. Organic Materials Can Build-Up Large Amount of SOM

Organic crop production has been proposed as a strategy for soil organic carbon (SOC) sequestration. Thus, advocates of organic fertilizers believe that organic materials build up SOM irrespective of the amounts they are applied to the soil. Organic materials no doubt supply nutrients and energy for soil micro-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 [36], as large quantities of organic materials as well as a long time 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.

Annual carbon input into the soil is the most important factor responsible to build and sequester SOC and crop production practices that result in higher biomass and yields can add more carbon to soil through above- and below-ground crop residues [61]. Since the above-mentioned evidences indicate that crop yields are generally lower in organic farming, it can be hypothesized that the carbon input through crop residues to soil would also be lower resulting in lower SOC sequestration and consequently lower SOM build-up in organic farming. This hypothesis has been proved to be true in many cases. For example, Lutzow and Ottow [62] and Petersen et al. [63] reported lower SOC in organically- than conventionally-managed farms while Burkitt et al. [64] and Leifeld and Fuhrer [65] demonstrated no difference in SOC between organically- and conventionally-managed farms. Thus, it seems clear from these studies that the magnitudes of increases in SOM due to addition of organic materials or organic fertilizers would be far less than what many advocates of organic fertilizers claim.

4.8. Chemical Fertilizers Cannot Build Up SOM

The critics of chemical fertilizers believe that such fertilizers cannot build up organic matter in soil. Some evidences however indicate that inorganic fertilizers, when applied at rates at which maximum yields are achieved, can also result in SOM build-up and microbial biomass by promoting plant growth and increasing the amount of litter and root biomass added to soil. Bijay-Singh [66] reported that only when fertilizer N is applied at rates more than the optimum, it can increase 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 [67]. High fertilizer rates however can adversely affect soil microbial biomass (see later).

4.9. Organic Materials Can Be Universally Applied

Advocates of organic fertilizers claim that it is always safe to apply organic materials on every soil, irrespective of amounts and SOM status, including the anaerobic flooded soils. The reality is that excess organic matter could cause zinc and sulphur deficiency especially when the field is continuously flooded [37,40]. In addition, toxicity from products of anaerobic decomposition (such as organic acids and hydrogen sulphide) could also be a concern. Hence, when the SOM in soils is relatively high (>4.0%), organic materials should preferably be applied in dry season or aerobic conditions [36,39].

4.10. Bio-Fertilizers Can Increase Nutrient Content of Soil

Soil organisms (bacteria, fungi, algae, *actinomycetes*, earthworms, etc.) are essential components of the soil, contributing to soil productivity. There are aerobic and anaerobic N_2-fixing bacteria (e.g., *Rhizobia*) and some other bacteria and fungi (e.g., *Trichoderma*), which are effective in decomposing or mineralizing SOM. These microorganisms can be used to dispose farm wastes and to improve soil productivity. Bio fertilizers, 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 solubilisation, or cellulose degradation [37]. Advocates of organic fertilizers claim that microbial fertilizers or bio fertilizers, containing organisms such as bacteria, fungi, algae, *actinomycetes* and so forth, contribute significant amount of nutrients to the crop and can be used to any crop or any type of ecosystems [36]. The fact is that bio fertilizers do not directly contribute nutrients but merely make nutrients available from other sources like atmospheric N_2 or SOM [37].

While the role of the bio fertilizers has been recognised, there are evidences regarding their inconsistent effects on crop growth or yield, or not as dramatic as claimed by the advocates of organic fertilizers. Moreover, since most of the microorganisms in bio fertilizers work under aerobic conditions, they may not be effective under anaerobic conditions. Conditions where bio fertilizers are effective are not defined properly to guide extension workers and farmers. Hence, it is important that the bio fertilizer developers indicate the species or strains of organisms present (whether aerobic or anaerobic) and the conditions where the product is effective.

5. Nutrient Supply from Inorganic and Organic Sources

It is a widely recognised fact that small and poor farmers in almost all countries of the world lack resources to purchase high-yielding inputs such as chemical fertilizers and hence rely on the organic inputs in whatever quantities already available in their farm. Organic nutrients are available in varying amounts (from low to high) in soil (i.e., indigenous nutrients) and/or through external sources (i.e., either inorganic or organic). In most cases (except some lowland rice fields), organic nutrients must be supplemented with inorganic fertilizers. Small farmers practising subsistence farming system and with limited income to purchase fertilizers can rely on organic inputs such as FYM, composts, or crop wastes and residues that are available in their farm [68]. However, such inputs contain very low amounts of nutrients which can only support very low-yielding crops. For transitioning from subsistence to commercial agriculture and to achieve high yields and high income, application of inorganic fertilizers is unavoidable.

Erisman et al. [69] reported that over 48% of more than 7 billion people are living today because of increased crop production made possible by applying fertilizer N. Hence, if sufficient amounts of nutrients, especially N, are not applied to plants, high yields will not be possible and transitioning to commercialization of agriculture will be a dream only. 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. As stated earlier, while inorganic fertilizers are crucial to increase crop yields, they ae generally not affordable by small-scale subsistence farmers of developing world. On the other hand, the soil-derived as well as the externally-supplied organic sources of nutrients will not be sufficient to achieve high yield. Hence, depending on their relative availability, nutrients need to be supplied in an integrated manner and in balanced proportions through both inorganic and organic sources.

For illustration purpose, nutrient supply through chemical fertilizers and most common 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^{-1}, respectively) is shown in Table 3. Rice, wheat and maize are chosen because these are the crops grown predominantly in all regions of the world and are globally important especially for achieving the food security of the growing population of the developing countries [32,35,60]. Their sustainable production is necessary in all 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 (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 contribute to nutrient cycling [68,70–72]. In the example, rice residues are applied to wheat and maize crops and maize residues are applied to the rice crop. The concentrations of N, P_2O_5 and K_2O in urea, TSP and MoP are 46.0%, 46% and 60%, respectively. As stated earlier, the nutrient contents in organic manures are variable and hence the mean values for FYM and crop residues, as shown in Tables 1 and 2, were used for the calculations. Nutrient requirements, predicted by the QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) model shows that for rice, wheat and maize, 14.6, 18.0 and 22.3 kg N, respectively, would be required to obtain 1 t of grain yield.

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 above crops [67,73–76].

Data in Table 3 reveal that when only chemical fertilizers are used to meet the requirements of high-yielding crops (Scenario 1), only small volumes of chemical 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 volumes or amounts of FYM and crop residues would be required to meet crop nutrient requirements and hence all the above issues would be significantly greater. In Scenario 2 and 3, where some fractions of the nutrients are used through organic sources, these issues would still be there but to the much lesser extent than in Scenario 4. The extremely large amounts of organic materials (FYM or other sources of animal manures or crop residues) as required for Scenario 4 and to the lesser extent for Scenario 2, simply would not be available in sufficient amount for organic farming in any country, also due to their multiple uses [68]. Miller [18] also reported that there is simply not enough cow manure in any country to fertilize the organic crops for high yield. Avery [13] also stressed that sewage sources of N would be only about 2% of the synthetic N used to fertilize the crops. The above calculations and the literature review clearly suggest that most countries would need extra lands and water to grow and produce organic materials and feed animals to produce enough quantities of plant biomass and manures to fertilise the soils for achieving high yields if the nutrients were to be supplied through organic sources only.

Our conclusions also agree with many previous workers [2,13,16,19,20,77,78], who all reported that huge amount of extra land would be needed if such sources of N were to be promoted. Except for some countries in Africa, extra lands would not be available in any other countries due to the ever-increasing population and need for housing, industry and other infrastructures. Even if lands would be made available to produce organic inputs, using only organic sources will be highly laborious, costly and impractical unless some novel or innovative practices are developed and used to build on-farm soil fertility and in-situ nutrient application. Further, as mentioned above, nutrient contents in organic materials are highly variable and release nutrients at variable rates. Hence, any assumptions on nutrient contents and release patterns lead to uncertainties in calculations of nutrient recommendations from organic sources. In most developing countries, information on period of nutrient release and on the rates by which nutrients are mineralized are not provided to farmers, further leading to uncertainties in calculations of nutrients supplied through such sources.

6. Need for Site-Specific Nutrient Management

Existing nutrient management recommendations for most crops in most developing countries often consist of one predetermined rate of nutrients for vast areas of production. Such recommendations assume that the need of a crop for nutrients is constant over time and space. However, the nutrient needs for supplemental nutrients for any crop can vary greatly among fields, seasons and years, because of differences in crop-growing conditions, water, nutrient and soil management and climate, resulting in large spatial and temporal variability in soil N supply. Hence, the nutrient management for crops aimed at high yields requires an approach that enables adjustments in nutrient application to accommodate the site- or soil-specific needs of the crop for supplemental nutrients. Site-specific nutrient management (SSNM), a plant-based approach and a form of precision nutrient management, is used to address nutrient differences which exist within and between fields by adjusting the nutrient application through chemical fertilizers or organic sources to match the site, soil, or season differences. SSNM approach for irrigated rice systems for South and SE Asia was developed by International Rice Research Institute (IRRI) in collaboration with National Agricultural Research and Extension Systems (NARES) partners in 1990s [79–81] to address serious limitations arising from blanket fertilizer recommendation for large areas. The approach focused on managing field-specific spatial variation in indigenous N, P and K supply and considering nutrient losses from soil, recovery efficiency of a given fertilizer and nutrient uptake and use efficiencies, temporal variability in plant N status occurring within a growing season and medium-term changes in soil P and K supply resulting from actual nutrient balance.

SSNM or precision nutrient management strategies, based on principles of synchronization of crop demand of nutrients with supply from all sources, including soil, fertilizer and organics, hold great potential for ensuring high yields of crops along with maintenance or improvement in soil health [39,60]. SSNM approaches have the potential to optimize nutrient management for cropping systems as farmers replace crops in their crop rotations. Based on the scientific principles, SSNM recommends nutrients for optimally supplying to crops as and when needed for specific field/soil and cropping season. Scaling-up of nutrient management technologies can be faster if simple computer-based decision support system (DSS) tools can be developed for use by farmers and extension workers from governmental and non-governmental organizations and from the private sector. One of such tools is Crop Manager for rice, maize and wheat developed by International Rice Research Institute (IRRI) (http://cropmanager.irri.org/) and similar other tool is Nutrient Expert for rice, maize, wheat soybean developed by International Plant Nutrition Institute (IPNI) (http://software.ipni.net/article/nutrient-expert). Both tools have been widely evaluated and promoted by IRRI and IPNI in partnership and collaboration with International Centre for Maize and Wheat (CIMMYT) and NARES of several countries in South and SE Asia and Sub-Saharan Africa [82–87]. These tools are available both on-line and off-line in mobile phones and laptops and are interactive and easy-to-use that can rapidly provide nutrient recommendations for an individual farmer's field in the presence or absence of soil testing data. Future approach should give priority for further refinements of simple DSS tools for integration and widespread delivery of improved and integrated nutrient management strategies for diverse agro-ecosystems of Asia, Africa and Latin America.

7. New and Alternative Approaches to Increase On-Farm Soil Fertility and Nutrient Supply

An important question in soil fertility management globally and especially in South and SE Asia and Sub-Saharan Africa, where very low amounts of fertilizers are used, is how crop biomass production can be increased. This is important to enhance surface cover and generate greater quantities of organic nutrients to complement or supplement whatever amounts of inorganic fertilizers a smallholder farmer can afford to apply. The calculations presented in previous section reveal that organic materials (or organic fertilizers) obtained from traditional crop or crop-livestock systems are not enough to improve soil fertility and meet nutrient demand of high-yielding crops. Alternative techniques (or some radical approaches) would be required if the aim was to supply larger proportion of nutrients from organic sources to restore and maintain on-farm soil fertility, obtain high yields and achieve food security for the ever-increasing global population. One of such approaches could be agroforestry system, which is defined as the integration of trees into annual food crop systems, using both perennial and annual species (trees, food and vegetable crops, etc.). In this system, farmers can grow crops and trees in right proportions so that crop residues and tree leaves can provide enough nutrients to build and maintain soil fertility, supply nutrients to plants and can provide green fodder to livestock [88,89]. Sanchez [89] called agroforestry system as "second soil fertility paradigm" which mainly focuses on improved fallow as well as biomass transfer technologies using trees and shrub legumes capable of fixing N_2 through their roots and from the biomass from their leaves and build and maintain soil fertility.

In recent years, more attention has been given to agroforestry system as a possible and sustainable solution to maintain soil fertility. Thus, to promote agroforestry system, a global alliance called Evergreen Agriculture Partnership, has been formed (http://evergreenagriculture.net/). Evergreen Agriculture, an advanced form of agroforestry system, is an approach for maintenance of a green cover on the land throughout the year in the tropical and sub-tropical climate. Such an approach of producing enormous amounts of biomass on-farm does not require extra lands for growing trees as they can be planted in same land together with crops. Depending upon which woody species are used and how they are managed, their cultivation in crop fields can bolster nutrient supply through

N_2 fixation and nutrient cycling, can build-up on-farm soil fertility and provide nutrients to plants as per their demand, enhance suppression of insect pests and weeds, improve soil structure and water infiltration, produce greater amount of food, fodder, fuelwood and fibre and obtain higher income directly from products produced by the intercropped trees and crops [90,91]. Authors suggest that such an intercropped system 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 CO_2 emissions and tackle climate change [90,91]. Evergreen Agriculture thus has potential to contribute to integrated soil fertility management and the knowledge to adapt these to local conditions that maximize use efficiencies of chemical fertilizers and organic resources and increase crop productivity. In this respect, the authors [90,91] suggest that the types of intercropped trees can 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 crops within the area that they occupy per unit area in the field.

The principles of Evergreen Agriculture have now been widely applied in sub-Saharan Africa where they have been adapted to a diversity of situations, often building successfully on proven indigenous farming technologies and where diversity and polyculture are a common feature of the agricultural systems [91]. For example, in several countries in sub-Saharan Africa, Evergreen Agriculture is practised with conservation farming with *Acacia albida* (or *Faidherbia albida* (Delile) A.Chev.), an indigenous N_2-fixing tree species. *Faidherbia* remains dormant and sheds its foliage during the early rainy season at the time when field crops are being established and re-growing at the end of the wet season, thus exhibiting minimal competition while enhancing yields and soil health. This unique growth habit, known as 'reverse leaf 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 near *Faidherbia* trees tend to exhibit improved performance and yield [59,92]. Other potential options for sub-Saharan Africa include intercropping maize with *Gliricidia sepium* (Jacq.) Kunth ex Walp., *Tephrosia candida* (Roxb.) DC., *Cajanas cajan* (L.) Millsp., or *Sesbania sesban* (L.) Merr. [59] but can also be recommended for South and SE Asia. For example, research in Africa has revealed that several tons of additional biomass ha^{-1} can be generated annually to accelerate soil fertility replenishment and provide additional livestock fodder and that such systems can result in dramatic increases in maize yield when grown in association with *Faidherbia* of varying age and density, agronomic practices and the weather conditions [92,93]. Akinifessi et al. [59] concluded that fertilizer trees such as *Faidherbia*, *Gliricidia* and *Leucaena* sp. can add 34–300 kg N ha^{-1} $year^{-1}$ through BNF and that, depending on crops, nutrient contributions from fertilizer tree biomass can reduce the mineral N requirement by up to 75%. 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 to increase crop yield, increase income and achieve food security.

Evergreen Agriculture could also be compatible with crop-tree-livestock integration which is practiced for decades by smallholder farmers in South and SE Asia (for e.g., for example, see Timsina et al., 1991 [68] for a description of crop-livestock and crop-tree-livestock integration for Nepal). This could also be compatible with the three principles of conservation agriculture (CA) (i.e., reduced or no tillage, residue retention on the soil surface and profitable and sustainable rotations) in situations where these are feasible and appropriate [42]. Although some implementation-related issues of CA remain to be addressed, it has now been adapted to many crops and areas in countries of South Asia [42–44] and Africa [94]. Research in Africa has also demonstrated that Evergreen Agriculture by integrating fertilizer trees and shrubs into CA can dramatically enhance both fodder production and soil fertility [91].

8. Conclusions and Research and Policy Implications

A brief review of organic and conventional farming and sources of nutrients in this paper demonstrates that yields of organic agriculture are much less than conventional agriculture and that the current organic sources of nutrients are not enough to increase crop yields required to feed global population. The review also identifies the fact that unless novel and innovative approaches are developed and promoted to build on-farm soil fertility, organic nutrients in the current state of global agriculture are not enough to provide same amount of food that can be produced from conventional agriculture. Integrated and/or site-specific precision nutrient management of inorganic and organic sources is crucial for sustainable soil fertility management and to achieve food security. The application of nutrients in a balanced proportion through organic and inorganic sources and based on SSNM principles can lead to further improvements in soil health and soil fertility and productivity. Based on the available scientific evidences and considering the non-availability of organic materials in sufficient amount in most countries, nutrients from inorganic and organic sources should preferably be applied at 75:25 ratio but the new and alternative concept of Evergreen Agriculture, as discussed in this review, has potential to supply inorganic and organic sources of nutrients at 50:50 or 25:75 ratio.

It is recommended that appropriately-designed field experiments in any country must be conducted to determine the soils and environmental conditions where the organic fertilizers can be effective to better guide and benefit farmers before promoting or spreading the use of organic materials or organic fertilizers. There is also a need to document the long-term fate of organic materials in different cropping systems. Finally, the review strongly recommends that a well-designed agroforestry system for sustainable intensification would be the most effective strategy for integrated soil fertility management and the Evergreen Agriculture, which has been adopted in many countries of Africa, could be introduced and promoted in countries of Asia and Latin America too. Evergreen Agriculture seems to be a sustainable strategy to improve on-farm soil fertility, increase crop yields, provide fodder to livestock and fuel wood to smallholding farmers residing in countries with tropical and sub-tropical climate and finally meet global food demand. In areas where trees are sparse, government policies should aim to increase tree plantation and promote agroforestry and Evergreen Agriculture in those countries. This will encourage farmers to plant trees and will also promote the use of organic materials for sustainable soil fertility management, increase crop yields and feed the ever-increasing global population.

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