American Journal of Experimental Agriculture
5(5): 400-418, 2015, Article no.AJEA.2015.041
ISSN: 2231-0606

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Nutritional Requirement and Management of Arabica Coffee (*Coffea arabica* L.) in Ethiopia: National and Global Perspectives

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Authors' contributions

This work was carried out in collaboration between both authors. Author AM designed the study, performed the statistical analysis, wrote the protocol, managed the literature searches and wrote the first draft of the manuscript. Author FI managed the analyses of the study. Both authors read and approved the final manuscript.

Article Information

DOI: 10.9734/AJEA/2015/12510
Editor(s):
(1) Marco Aurelio Cristancho, National Center for Coffee Research, CENICAFÉ, Colombia.
Reviewers:
(1) Weverton Pereira Rodrigues, Center for Agricultural Science and Technology; Northern Rio de Janeiro University, Brazil.
(2) Anonymous, New University of Lisbon, Portugal.
Complete Peer review History: http://www.sciencedomain.org/review-history.php?iid=738&id=2&aid=6570

Review Article

Received 2nd July 2014
Accepted 16th August 2014
Published 22nd October 2014

ABSTRACT

The bulk of coffee soils in southwestern and southern regions of Ethiopia are classified as Nitto sols, which are highly weathered and originate from volcanic rock. These soils are deep and well drained having a pH of 5-6, and have medium to high contents of most of the essential elements except nitrogen and phosphorus. Also, most of the coffee plantations are often managed with shade trees in small scale, with minimal fertilization; litter fall and decomposition play an important role in nitrogen cycling and maintenance of soil fertility. The amount of plant nutrient required by coffee trees may vary depending on several factors. the amount and distribution of rainfall, the species and amount of other plants grown in association with the coffee trees, seasonal variation, topography, soil type and the prevailing cultural practices. Proper coffee nutrition requires special attention of the grower because it affects bean size (grade), bean quality and the overall productivity of the crop that determines marketability. Nutrients are applied to replenish those that are lost through tissue formation, yields, leaching and those that form compounds where they cannot be easily extracted by roots. This calls for application of mineral fertilizers and/or organic

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manures so as to apply the necessary nutrients in the required amounts. As a result it was possible to come out with a set of recommendations that are of immense value to the growers. Therefore, the objective of this paper is to review the achievements and constraints of mineral fertilization and the potential to use of organic/bio-fertilizers for the present and future coffee production in Ethiopia.

Keywords: Mineral fertilizes; bio-fertilizers; soil and plant tissue analysis; organic coffee; integrated nutrient management.

1. INTRODUCTION

Ethiopia holds a unique position in the world as *Coffea arabica* L. has its primary centre of diversity in the south-western highlands of the country. Today in a few remaining rainforests of western, southwestern and southeastern Ethiopia, coffee grows as an understory shrub in a large diversity and has maintained its own genetic diversity as a natural gene-bank. It continues, however, to survive all attacks by pathogens and pests in a unique way under natural conditions. Research findings over the past few decades revealed that there is a huge genetic variation for different agronomic traits among accessions of *Coffee Arabica* in Ethiopia. However, during the last 40–50 years, significant reduction of genetic diversity has occurred in the Ethiopian coffee due to deforestation and competition for arable land to expand food crops that coupled with rapid population growth [1,2,3,4].

Coffee production systems in Ethiopia are grouped into four broad categories namely, forest coffee, semi-forest coffee, garden coffee and coffee plantations [5]. They account 10, 35, 50 and 5% of the total production, respectively and mainly found in southwestern and southern Ethiopia. Garden coffee production system accounts the majority of production and is owned by small holder coffee growers which is produced in plots of varying sizes around dwellings. In this system, coffee is planted and managed in the farmer's backyard within small area and planted at low densities, ranging from 1,000 to 1,800 trees per hectare, is mostly fertilized with organic waste and is intercropped with other crops [4]. It is mainly found in southern, south western and eastern parts of the country; Sidamo, Gedeo, Keficho, west Harerge and west Wellega Zones. The traditional cultural practices implemented by the growers in most cases led to mismanagement of the soil and would result in serious land degradation and a rapid nutrient depletion that significantly influence coffee yield. The overall productivity of the crop is very low in traditionally managed coffee ranging from 450 to 472 kg/ha of clean coffee [5].

In the major coffee growing areas, most soils are exposed to nutrient leaching over a long period resulting in low organic matter content and require careful management to support good crop yields.

However, 85% of Ethiopian farmers don't use inorganic fertilizers while the rest add it at levels significantly below the recommended rate [6]. The bulk of coffee soils in the southwestern and southern region are classified as Nitro sols, which are highly weathered and originate from volcanic rock. These soils are deep and well drained having a pH of 5-6, and have medium to high contents of most of the essential elements except nitrogen and phosphorus [7]. Most of the coffee plantations are often managed with shade trees and minimal fertilization. Hence, from the point of view of nitrogen cycling, litter fall, and decomposition may play an important role in the maintenance of soil fertility [6]. This review therefore needed to supply necessary information on the achievements and constraints of fertilizer use (mineral and organic) in some major coffee areas of Ethiopia and to evaluate the past research recommendations in coffee nutrition by considering the nutrient dynamics with respect to climate change scenarios, that would be helpful for further amendment of nutritional status in most of the coffee growing areas.

2. MATERIALS AND METHODS

All institutions in Ethiopia that are involved in coffee research and development were contacted in 2012/013 and supplied the necessary information for Arabica Coffee nutrition. This was supported by interviews with key informants and by reviewing secondary data from reports of the research institutions. The data showed the past and present situation in coffee nutrition and trends in application of organic and mineral fertilizers for Arabica Coffee. We focused on producing data base to be made available on the present and future dynamics of coffee nutrition, so that the information should be web based and accessible by any of the institutions anywhere that helps to amend plant nutrition for coffee plant with respect to nutrient depletion with time. Also, reviews on coffee nutrition from global perspectives were included in this paper to compare the national research trends in coffee nutrition. Readers are referred to original articles on Ethiopian coffee research and research articles browsed from online libraries for detailed analytical methods and interpretation of results; all resources used for this review are duly cited.

3. ARABICA COFFEE PLANT NUTRIENT MANAGEMENT IN ETHIOPIA

The importance of proper coffee nutrition cannot be over emphasized because nutrition affects bean size and bean quality, both of which determine the value of the coffee produced. It is worth remembering that for optimum growth and productivity, the coffee plant requires adequate nutrients. Nutrients are applied to replenish those that are lost through tissue formation, yields, leaching and those that form compounds where they cannot be easily extracted by roots. This calls for application of fertilizers so as to apply the necessary nutrients in the required amounts [8].

The amount of plant nutrient required by coffee trees may vary depending on several factors. The amount of rainfall and its distribution, the species and amount of other plants grown in association with the coffee trees, seasonal variation, the topography, the soil type and the prevailing cultural practices are a few. Estimation of the nutrients required by the new crop is based on soil and plant tissue analysis [7].

The components of mineral fertilizers are divided into macro and micro based on their requirement by the plants. Macro nutrients (N, P, K, Ca, Mg, and S) which are required by plants in large quantity more than 1ppm are most important for the growth of the coffee plant. Besides, there are micro nutrients (Fe, Mn, Zn, Mo, Cu, B, Al) that are demanded by plants in much less quantity (less than 1ppm) but without them problems in growth may arise. Most soils are endowed with sufficient amount of trace elements and thus, there is hardly any need for their application [8].

According to [9], in the past three/four decades, extensive fertilizer trials were carried out at Jimma Agricultural research Center and its sub-centers that represent the major coffee growing agro-ecologies of the country. As a result it was possible to come out with a set of recommendations that are of immense value to the end users.

3.1 NPK Fertilizer Management

Very little work has been done on the mineral fertilization of coffee in Ethiopia before1970's. One of the first fertilizer experiments on coffee at Jimma Research Center (JRS) was carried out to supply the necessary information for Coffee and Tea Development Authority (CTDA) in connection with the coffee improvement project and replanting program. Different nitrogen, phosphorus and potassium rates were investigated in factorial combination [10].

3.2 Nitrogen Management

Nitrogen is one of the essential plant nutrients required by the coffee tree in large quantities as compared to other nutrients. In an effort to determine the optimum nitrogen rate for coffee production in different agro-ecologies, various fertilizer trials were accomplished at the main center (JRC) and sub-centers or trial sites (Gera, Metu, Tepi, Bebeka, Wonago, and Bedessa). At JRC, the response of coffee trees to applied fertilizer was investigated since early 1978/79 [11]. The results reported show significant coffee yield increment with increasing level of nitrogen. The most noticeable yield response of coffee was for 150kg/ha nitrogen [11]. Paulos [7,9] has summarized results of pervious fertilizer trials at different coffee growing areas of south-western Ethiopia in which the highest yield of coffee was recorded in response to the highest rate of nitrogen (300kg/ha) (Fig. 1), with significant yield reduction for further increases of nitrogen.

3.3 Phosphorus Management

Phosphorus in known to be one of the most recognized limiting factors for coffee production in most soils of south western Ethiopia. The soils highly weathered, low in pH, high in iron and aluminum contents leading to high phosphorus fixation [12]. Significant yield responses were reported from different fertilizer trials conducted at JARC. From a field experiment at Melko, a 50% increase in coffee yield was reported when the level of potassium was raised from zero to 33kg/ha, but further increase in the level of this nutrient was not reflected in increased yield [11].

On the other hand, no significant yield was reported from similar experiments at Gera, Tepi, and Metu [11,12].

At Wonago, the response to mineral fertilization was examined on a 30-year old forest coffee [13]. The combined analysis over years indicated significant yield response of coffee to NP fertilization. The optimum NP rate found in the study was varieties were recommended [13]. In general a positive correlation between coffee yield and phosphorus fertilizer application at different areas was reported [7,9]. Coffee yield increment due to phosphorus (33kg/ha) application at Melko was 597 kg (64.5%) over the control (Fig. 2). It was also indicated that the interaction between N and P gave better results than the main effects alone.

3.4 Potassium Management

Potassium fertilizer application is not common in Ethiopian Agriculture, whether in treecrops like coffee or in cereal crops. This is due to the view that potassium is not alimiting nutrient in Ethiopian soils, a conception, which is often based on the report by Hofner and Schmitz (1984) cited in [6]. However, Ethiopian Agriculture is a highly exploitative type in which plant nutrients particularly potassium are heavily extracted or mined from the soil and very little or no crop residues are returned back [6].

Results from some trials involving potassium fertilizer also indicate positive crop responses to potassium application [7,12].

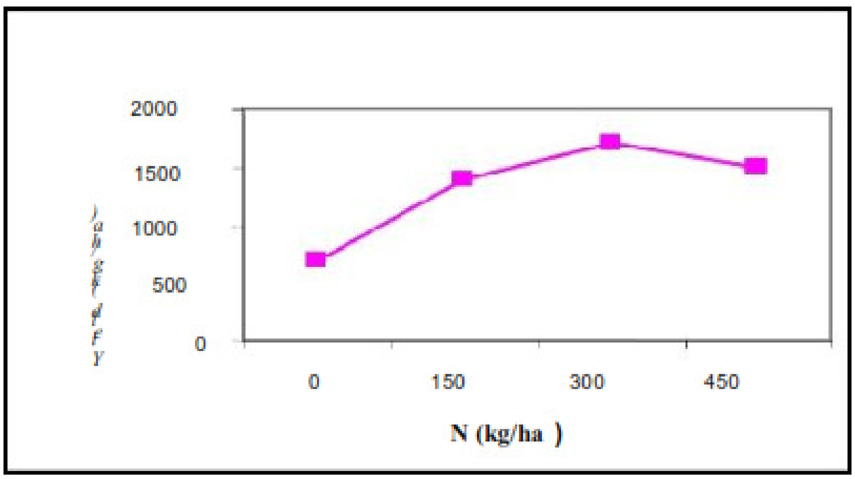

Fig. 1. Effect of N on coffee yield at Melko [7]

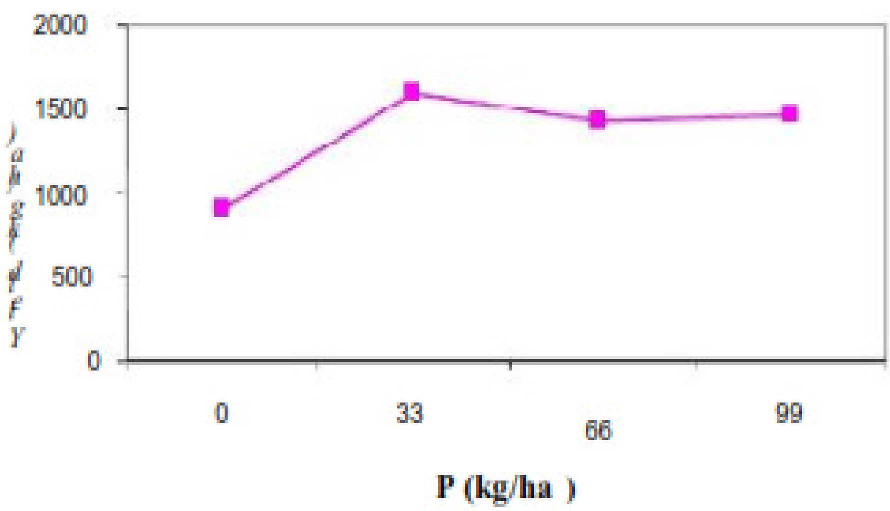

Fig. 2. Effect of Phosphorus on coffee yield at Melko (Paulos, 1986)

In a fertilizer experiment at Melko, significant coffee yield improvement was noticed (Fig. 3), when the level of potassium was increased from zero to 62 kg/ha, but further levels of potassium did not result in increased yield [7,12]. On the other hand, in a similar experiment at Gera, Metu, and Tepi, results indicated no significant fertilizer effect on coffee yield [11,12].

3.5 Phosphorus Status of Long-Term Fertilized Soils

Unlike nitrogen, phosphorus is relatively immobile in the soil. Hence, repeated application of phosphorus fertilizers for a long time might result in the accumulation or build-up of the nutrient in the soil where further application of phosphorus fertilizers will not have significant effect on yield. This is especially important for research plots used for fertilizer trials. An experiment was carried out at Melko to examine the status of phosphorus and other nutrients in response to long-term fertilizer applications in soils cropped to coffee [14]. The data indicated build up of phosphorus and reduction in soil pH because of long-term fertilizer application (Table 1). The result therefore, confirmed the imbalance of nutrients caused by continuous application of inorganic fertilizers. Such a build-up in phosphorus fertilizer result in imbalance and make it difficult for future fertilizer trials. Hence, fertilizer studies involving phosphorus need to be carried out at places where the levels of P and soil acidity do not present similar problems.

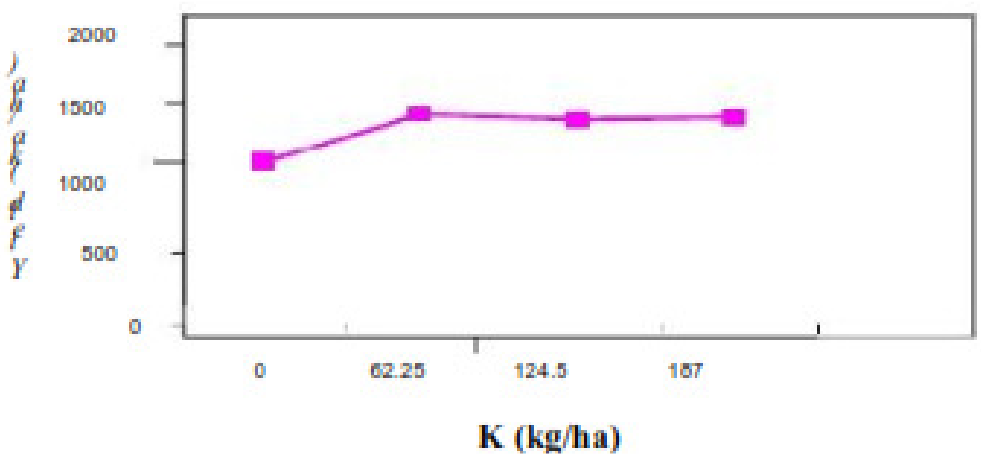

Fig. 3. Effect of potassium fertilizer on coffee yield at Melko [7]

Table 1. Effect of long-term fertilizer application on soil fertility status

Sites	pH	N (%)	P (ppm)	K (Meq/100g)	C (%)	CEC	DTPA- Soluble micronutrients (ppm)			
							Fe	Mn	Zn	Cu
1	6.0	0.18	7.2	0.93	1.8	34.6	32.8	148.2	2.8	3.2
2	5.2	0.22	23.8	1.13	2.7	26.6	58.1	124.5	3.3	3.7
3	4.8	0.21	15.8	0.53	2.8	32.4	46.5	131.5	2.3	3.7
4	4.9	0.21	24.1	0.50	2.5	30	49.8	155.9	2.7	3.1
5	5.5	0.27	36.6	1.08	3.0	28	52.8	101.8	2.9	3.1
6	4.7	0.22	82.4	0.71	3.9	23.6	63.2	219.1	5.5	4.5
7	5.5	0.21	65.3	0.66	3.5	28.2	61.9	131.9	3.0	2.7
8	6.1	0.22	40.6	0.89	3.5	27.6	68.4	172.6	3.3	4.2
9	5.7	0.22	3.6	0.67	3.6	27	32.4	157.2	1.9	3.2
10	6.1	0.18	2.8	0.78	3.3	29.6	48.9	109.1	2.1	3.3
SD	0.53	0.03	26.72	0.27	0.63	3.10	3.8	10.8	0.34	0.74
SE	0.17	0.01	8.06	0.10	0.2	0.98	1.21	3.41	1.1	0.6

Sites 1-8: Fertilized 15 to 20 years, and sites 9-10: From unfertilized adjacent fields N-nitrogen, P-phosphorus, K-potassium, pH-power of hydrogen, CEC- Cation Exchange Capacity, DTPA – Di-ethylenetriaminepenta- acetic acid, Fe-Iron, Mn-Manganize, Zn- zinc, Cu- copper, C-carbon . [14]

On the other hand, the level of micronutrients was found to increase in long term fertilized than unfertilized indicating the enhancement of solubility and hence availability of these micronutrients with the reduction of the soil's pH. In general, considering the imbalance of nutrients and reduced soil pH, corrective measures should be sought instead of emphasizing the increased micronutrient availability in long-term fertilized soils since visible and critical micronutrient deficiency has not been noticed in the area so far [14].

3.6 Time and Methods of Fertilizer Application: Growers Practice

The most commonly used fertilizers for coffee (as source of nitrogen, phosphorous and potassium) are urea, diammonium phosphate (DAP) and potassium chloride (KCl) respectively [6]. Urea (CO $(NH_2)2$, 46% N) and diammonium phosphate (NH_4) 2 HPO, 20%P and 18%N) are widely used in the country. Currently other inorganic sources of N, P and K are being investigated for different agro-ecologies and crop types in the country. Such fertilizers include calcium ammonium nitrate, triple supper phosphate, and rock phosphate. Micronutrients are applied only rarely in large coffee plantations that has the technical and financial strength to afford such practices [6]. The most widely used phosphorus containing fertilizer is diammonium phosphate (DAP) and rarely triple supper phosphate (TSP). When used for trees, these fertilizes should be applied at establishment period and in mature condition. The most favorable time of application (especially under southwestern Ethiopian condition is in March/April, in the rainy season, and at the end of the rainy season in September. After application, the fertilizer should be totally incorporated in to the soil so that losses through volatilization can be minimized [6].

Urea, the most popular source of nitrogen, is easily available in the market, hence commonly used for coffee plantations in different parts of the country. It is known that a significant proportion of the applied nitrogen may be lost as ammonia within a few days after application [6]. Therefore, it is advisable to split the recommended dose of nitrogen fertilizer into three or four equal parts to increase the fertilizer use efficiency. The fertilizer should be applied when the soil is moist; hence, the most convenient time to apply the fertilizer is during March/April, June/July, and September [8]. Maximum care should be taken during application not to apply under mulch and weed cover, and have some distance from the main trunk but under the canopy.

Nevertheless, using mulch after fertilizer application is useful in that it contributes to minimizing the nitrogen loss. Therefore, urea should be incorporated with the soil to avoid volatilization loss. Incorporation of urea into soil can minimize ammonia loss by increasing the volume of soil to retain ammonia [6]. Some investigations have indicated that the continued use of one type of nitrogen fertilizer might alter the optimum pH range of the soil; hence, alternating the use of different fertilizers such as Urea, ammonium sulphate nitrate (ASN), or calcium-ammonium nitrate (CAN), if they are used help to maintain the optimal range of soil reaction in the area. Application of potassium fertilizer is not common in the smallholder coffee production, but it is used in the big coffee estates or plantations. Murate of potash (KCl) and sulphate of potash (K_2 SO_4) are commonly found on the market. The time of potash application is at the beginning and the end of the rainy season. Potassium should be applied within the root zone the trees on weed and mulch free area [6].

3.7 Fertilizer Rate Recommendations

In the past three to four decade, extensive fertilizer trials were carried out at Jimma Research Center and its sub-centers that represent the major coffee growing agro-ecologies of the country. As a result, it was possible to come out with a set of recommendations (Table 2) that are of immense value to the grower. Fertilizer application depends on various factors including: type of production systems (forest, garden, open, low shade), soil fertility status and soil reaction, type of coffee variety (local, high yielding), age of the coffee tree and plant population. Open and low shade coffee plantations, high yielding varieties and mature trees on poor soils (low fertility) should be given the full dose of the recommended fertilizers. On the other hand, forest coffee, low yielding and young trees (less than three years), rich soils (fertile soils) lower amount than the recommended full dose [15].

3.8 Verification of Fertilizer Rates

On-farm Verification trials were carried out in different coffee growing areas to verify the recommended fertilizer rates for coffee production [16]. The result indicated that the highest clean coffee yield obtained at sites in Jimma and Metu areas was in response to the recommended rates of 172 and 63 Kg/ha nitrogen and phosphorus fertilizers respectively.

In addition, around Jimma, yield of coffee trees treated with potassium fertilizer (62kg/ha) showed significant increase over the control and half dose of the recommended NP fertilizer rate (Table 3).Therefore, the significance of the results obtained was not only application of recommended nitrogen and phosphorus fertilizer rates; but also with application of potassium. This stressed the need of more vigorous and comprehensive approach in research activities focusing on the potassium requirement of the coffee plantations in the region with special attention to improvements in yield and quality characteristics.

3.9 Fertilizer Management Problems

The fertilizer recommendation reviewed in this paper has been given for the commonly used coffee varieties that were under propagation since the trial was carried out decades ago. Currently many varieties are released for users, which might have different response or requirement to mineral nutrition. Moreover, the nutrient status of most soils is expected to change after such a long period since fertilizer trial has been carried out. Therefore, the challenge faced now is that of updating or recalibrating the fertilizer recommendations already given for the traditional varieties and to the newly released coffee hybrids and selections [6].

Fertilizer application is not a common practice in the smallholder coffee production; when applied, it is even very much below the recommended rates. It is known that, not only the amount of fertilizer applied but also its management is also very important for increasing the productivity and fertilizer use efficiency. A significant proportion of the applied nitrogen may be lost as ammonia within a few days after application. Therefore, proper management can result in significant reduction of the losses. The efficiency of urea, the most commonly used nitrogen fertilizer is very low. It is however clear that the most prominent problem of fertilizer use in Ethiopia, is the ever increasing and prohibitively high fertilizer cost. On the other hand, soil acidity and low soil nutrient levels especially that of nitrogen and phosphorus continued to be challenges for the research system and development endeavors in most places where coffee is dominantly grown in southwestern Ethiopia [6].

Table 2. Location specific NPK fertilizer recommendations for coffee, [15]

Location	Recommendation domain	Recommended Rates (Kg/ha)		
		N	P	K
Melko	Jimma, Manna, Seka, Gomma, Kossa	150 - 172	63	0
Gera	Gera	No	No	No
Metu	Metu Hurumu, Yayou, Chora	172	77	0
Tepi	Tepi	172	77	0
Bebeka	Bebeka	172	77	0
Wonago	Wonago, Dale, Aleta, Wondo, Fiseha Genet	170 - 200	33 - 77	0
Bedese	Habro, Kuni, Darelebu	150 - 235	33 - 77	62

Table 3. The effect of NP- fertilizer treatments on the yield of coffee around Jimma EARO [16]

Treatment (Kg/ha)	Clean Coffee Yield (qt/ha)			Mean
	1996	1997	1998	
Control	10.2	11.52	9.42	10.38
$N_{862}P_{31.5}$	9.77	10.92	12.35	11.02
$N_{172}P_{63}$	15.67	13.72	21.47	16.95
K_{62}	14.12	12.37	12.82	13.11
LSD (0.01)				4.03
SE (±)				2.06
CV (%)				27.77

4. MINERAL AND ORGANIC FERTILIZERS MANAGEMENT: GLOBAL PERSPECTIVES

4.1 Essential Minerals and Their role in Coffee Plant

Coffee plants have high N and K requirements [17]. There is a close relationship among nitrogen supply, number of leaves, and number of flower buds [18]. Whereas adequate tissue N levels are favorable for starch and other carbohydrate production needed for fruit formation and growth, in deficient plants symptoms develop particularly when the berries grow [19]. Potassium also plays a major role in coffee plant physiology especially during fruit growth and maturation. The K quantity exported at harvest exceeds that of N which helps to explain why it can become limiting after a few years [1]. A good correlation exists between the K status, as measured by leaf content, and stored starch and yield. When tissue K is adequate the proportion of floats and branches with symptoms of overbearing decreases [19].

The remobilization and re-utilization of certain nutrients is an important metabolic feature during development or in cases of seed germination, under stress conditions in the period of vegetative growth and the reproductive stage as well and, in the case of perennials, before leaf fall. As indicated by deficiency symptoms which develop in the leaves, the degree of both N and K mobilization is large [20]. There is a lack of studies dealing with N and K transport from organs of residence towards other ones, either vegetative or reproductive or both, under normal or deficiency conditions. The development of isotopic techniques has allowed better understanding of the mechanism involved in the uptake and transport of nutrients directly related to productivity increase and sustainability. In the present contribution the isotopic dilution technique was used with the stable isotopes ^{85}Rb for potassium. ^{15} N for nitrogen and N is intensively used as a tracer in soil-plant system studies. It has also been shown that ^{85}Rb, a stable isotope, can be used as a tracer for K [21].

Hydrated potassium and rubidium have a similar ionic radius and both cations occupy the same binding sites on the plasma membrane of root cells [22]. Although Rb cannot replace K in its metabolic roles, rubidium is capable of replacing potassium in proton transfer at the tonoplast level [20]. ^{86} Rb has been used in biological research as a tracer for K [23,24]. The use of ^{42}K in experiments of short and medium duration is practically impossible due its unsuitable half-life (12.4 hours as opposed to 18.7 days for Rb), and low specific activity [25]. The stable isotope ^{85}Rb, on the other hand, has proved to be a safe and adequate tracer, notwithstanding the experimental period length.

4.2 Soil and Leaf Analysis for Determination of Best Nutrition Practices

Nutrients are recycled within the environment. A 'closed' environment such as a rainforest recycles its own nutrients and is more or less self-sufficient [26]. However, where plants are grown in a commercial situation, it is necessary to replenish the nutrients that are removed from the system. Without additional nutrients in some form of fertilizer, coffee yields will remain very low as nutrients are removed with the coffee beans [13].

Un-shaded plants of dwarf, high-yielding varieties such as Catimor, will quickly develop dieback and die if adequate nutrients and water are not added to the soil [27]. Plants with mild to moderate dieback will recover with timely good fertilizing, watering and weed management. To help determine the best nutrition practices, soil and leaf analyses are recommended [28].

4.3 Optimum Leaf and Soil Nutrient Levels

Once the soil and leaf samples have been taken (Tables 4 and 5), it is important to analyze the results and compare them to levels that have been determined as optimum in coffee plantations around the world in order to devise a nutrition program for the coffee [28,17].

4.4 Nutrient Uptake by Different Plant Parts

Lima Filho and Malavolta [17] studied the mineral nutrition of mature Arabica coffee plant under greenhouse conditions using both normal and deficient young coffee plants in Brazil. As indicated, the data from the first harvest, before flowering when all plant parts were labeled by ^{15}N and ^{85}Rb isotopes derived from the substrate showed that flower buds had a N level 30% higher than the leaves, whereas their K content was 31% lower. Nearly half of the plant N was in

Table 4. Optimum leaf nutrient levels for coffee plant. [17]

Nutrient	Optimum range
N (Nitrogen)	2.5 - 3.0%
P (Phosphorus)	0.15 - 0.2%
K (Potassium)	2.1 - 2.6%
S (Sulphur)	0.12 - 0.30%
Ca (Calcium)	0.75 - 1.5%
Mg (magnesium)	0.25 - 0.40%
Na (Sodium)	< 0.05%
Cu (Copper)	16 - 20 mg/kg
Zn (Zinc)	15 - 30 mg/kg
Mn (Manganese)	50 - 100 mg/kg
Fe (Iron)	70 - 200 mg/kg
B (Boron)	40 - 100 mg/kg

Table 5. Optimum soil nutrient levels for coffee plant [28]

Nutrient (extraction method in brackets)	Suggested optimum soil levels
pH (1:5 soil/water)	5.5 - 6.0
Organic matter (Walkley Black)	1 - 3 %
Conductivity (I:5 soil/water)	< 0.2 dsm
Nitrate nitrogen (1:5 aqueous extract)	> 20 mg/kg. Leaf tests more relevant
Phosphate (Colwell or bicarb)	60 - 80 mg/kg
Potassium (Ammonium acetate)	> 0.75 mg/kg
Sulphur (KCl-40)	> 20 mg/kg
Calcium (Ammonium acetate)	3 - 5 meq/100 g
Magnesium (Ammonium acetate)	> 1.6 meq/100 g
Aluminium (Potassium chloride extract)	Unknown but very low
Sodium (Ammonium acetate)	< l.0 meq/100 g
Chloride (1:5 aqueous extract)	250 mg/kg
Copper (DPTA)	0.3 - 10 mg/kg
Zinc (DPTA)	2 - 10 mg/kg
Manganese (DPTA)	< 50 mg/kg
Iron (DPTA)	2 - 20 mg/kg
Boron (hot calcium chloride)	0.5 - 1.0 mg/kg (sandy loams) 1.0 – 2.0 mg/kg (Clay loams)
Cation exchange capacity	3 - 5 sandy soil > 10 heavy soil types
Cation balance	Potassium (< 10%) Calcium (65 - 80% Magnesium (15 - 20% Sodium (< 5%) Aluminium (< 1%)
Calcium: Magnesium ratio	3 - 5

N.B. Different extraction methods would give different results and different optimum levels [28]

the leaves (45.9%); roots came next (32.9%). Branches and flower buds had 10.6% each. In the case of K, 53.1% was in the leaves, with 32.6% in the roots, whereas branches and flower buds had only 7.8% and 6.4%, respectively. The excess abundance of ^{85}Rb and the percent of excess ^{15}N atoms in the several parts showed low coefficients of variation. There was high enrichment for both isotopes, made necessary due to the expected dilution caused by plant growth 10 months after labeling. Within this period plants with adequate N and K nutrition increased their dry matter fourfold.

Similar report of Leaf Analysis [22] was carried out at the final harvest in fruit-bearing branches of N or K deficient plants showed a 30% drop in N level, and one of 67% in K concentration in relation to the adequately supplied plants. Normal plants had 23 mg kg $^{-1}$ N and 25 mg kg $^{-1}$ K, whereas the deficient ones had 16 mg kg^{-1} and 6 mg kg^{-1}, respectively. The more pronounced K-level drop was not accompanied by a proportional decrease in plant dry matter and fruit production. Average yield of the N and K deficient plants was similar. Meanwhile the vegetative biomass of the potassium deficient plants was higher than that of the N deficient ones (Table 6).

In all treatments the lowering of the N and K content in leaves produced either before or during the isotopic enrichment period, through the reproductive process was due to export into fruit and new organs during leaf senescence. Leaf fall also represented additional total N and K loss. Potassium and nitrogen are highly phloem mobile elements, and their re-utilization leads to rapid decline in their level in vegetative parts, thereby inducing earlier senescence [20]. Thus, nitrogen deficient plants grew less and produced fewer leaves, branches, and roots. Plants with adequate nutrition yielded, on the average, 56 g of dry fruits. Also, as reported [22] that potassium deficient plants produced nearly 50% less and those deficient in nitrogen produced 40% below normal. There was, however, a marked lack of uniformity in fruit formation which caused a high coefficient of variation insofar as yield is concerned. For this reason the statistical analysis failed to show significant differences among treatments.

The statistical test does not take into consideration the fact that 80% of the coffee plants adequately fed with both N and K yielded more than 10 g dry fruits, and 60% of such plants had a production higher than 50 grams. On the other hand, the N and K deficient treatments showed yields lower than 10 g in 46 and 58% of the parcels, respectively. Yields higher than 50 g were registered only in 18% and 17% of the N and K deficient plants, respectively.

Nutritional status at final harvest showed that the concentrations of N, K, and Rb (Table 7) in the several organs as a function of the treatments [17]. As indicated, the Nitrogen deficient plants suffered a 24% reduction of that element in leaves of the later flushing and in branches of both flushes. Leaves from the earl y flush had a 34% reduction in N level. The drop in fruit N averaged circa 45%. Root N was not affected by the limitation in N supply in the substrate. This is probably due to the fact that the main source of nutrients for phloem loading are branches and leaves, from which remobilization takes place, with reproductive and growing vegetative organs acting as drains [17]. In the case of K deficient plants, leaves from the early flush and root as well showed an almost 40% drop in the content of that element. Leaves and branches of the later flush showed a 45% and 30% drop, respectively. The lowest reduction in K concentration, around 16%, took place in the branches of the early flush.

The K/N ratio was variable according to the organ considered and the period of its formation, i.e., before or after differentiation of flower buds: leaves from the early flush – 0.5, leaves from the later flush – 0.8; branches from the early flush – 0.7, branches from the later flush – 1.4; roots – 0.9, fruits – 1.1; general average – 1.0. Before flowering the ratios were: 0.7 for leaves, 0.5 for branches, 0.6 for roots, and 0.4 for flowering buds; general average 0.6. This means that the N buildup in relation to K tends to decrease in the whole plant during the period of fruit growth. This finding is well defined in the branches of the later flush and in the roots. Before flowering, the total N content was 60% higher than that of K, whereas during the fruit ripening stage, the content of both nutrients was similar in the fruits and in the total as well.

Taking into account the existing reserves in the flower buds, there was an average 133% increase in the reproductive apparatus N content of the normal plants, against an almost 30% decrease in the deficient ones. On the other hand, there was a 530% increase in K content of the fruits of the well-supplied plants, and one of 127% in those from K deficient plants. The N quantity decrease which took place in the deficient plant reproductive organs between the stages of flowering buds and berry is due, in part, to the presence of few of the first, which had failed to develop, and mainly to the severe reduction in fruit N in relation to that of flower buds, which was 3.6 times lower, accompanied by a dry matter increase of only 180% [17].

Similarly, nutritional status influences both distribution of freshly absorbed elements and remobilization of previously acquired ones. These processes, therefore, play a fundamental role in the relationship between nutrient content and growth [28]. The utilization of N derived from the reserve organs by those formed after flower initiation and differentiation in the deficient plants was markedly higher than in those well supplied with that element. In the organs of reserve of N deficient plants a higher proportion of the element was taken up before the differentiation of flower primordia. This suggests that in the deficient plants N absorbed from the nutrient solution was preferentially transported to growing organs in a proportion much higher than that found in the well nourished plants [29].

Table 6. Dry matter of the various parts of coffee plant at final harvest [22]

Nutritional Status		Leaves		Branches		Roots	Fruits			Total
		Anterior flash	Posterior flash	Anterior flash	Posterior flash		Greens	Ripe	Total	
					g plant $^{-1}$					
NK-normal	Average	14.06*	97.45a	126.76a	53.04a	112.36a	15.48a	45.39a	56.22a	464.55a
	C.V. %	102.5	22.2	11.9	27.9	18.3	190.7	97.9	85.0	12.0
N-deficient	Average	21.84a	72.18b	98.76b	21.87b	83.79b	1.87a	32.21a	33.14a	328.58b
	C.V. %	103.6	18.3	13.0	25.0	14.3	53.7	133.4	131.2	12.8
K-deficient	Average	11.35a	94.85a	121.44a	48.30a	116.80a	1.90a	27.67a	292.3a	422.31a
	C.V. %	49.3	15.6	12.0	19.6	17.6	89.6	151.1	143.0	7.4

**Values followed by different letters on the vertical are statistically different (Tukey) at 1% level*

Table 7. Total content of N, K and Rb (mg kg^{-1}) in organs of the flushes before and after labeling with ^{15}N and ^{15}Rb [17]

Nutritional Status		Leaves		Branches		Roots	Fruits	
		Anterior	Posterior	Anterior	Posterior		Green (enlargement)	Ripe (berry)
				Nitrogen				
N-normal	Average	25.6	20.5	7.6	9.7	22.0	22.3	18.9
	C.V.%	16.9	12.7	3.5	11.5	16.1	15.4	13.9
N-deficient	Average	16.9	15.6	5.8	7.4	21.7	12.0	11.0
	C.V.%	6.9	5.6	11.0	6.1	7.3	3.9	8.7
				Potassium				
K-normal	Average	11.8	15.7	5.7	13.3	21.0	21.3	20.5
	C.V.%	37.2	15.2	22.8	17.3	23.5	5.7	3.7
K deficient	Average	7.2	8.6	4.8	7.4	1.31	14.8	14.5
	C.V.%	19.2	15.0	11.0	15.4	18.8	11.2	7.0
				Rubidium				
K-normal	Average	1.6	1.3	0.7	1.0	2.2	2.7	2.5
	C.V.%	38.0	22.2	26.5	18.2	29.6	15.1	12.5
K-deficient	Average	1.5	1.6	0.9	1.9	3.2	3.9	3.7
	C.V.%	22.1	21.8	17.7	19.0	18.7	15.7	16.8

During fruit ripening N is found mainly in the roots besides leaves from the later flush and fruits. The NR (remobilized) quantity in the fruits is a function of the load, reaching up to 25% of the total N in the case of well-fed plants. In the deficient plants the value is lower by nearly 15%. The reproductive organs represent an important drain: root activity and nutrient uptake decrease because less carbohydrates are supplied, being preferentially directed to the fruits [30].

The export of reserve K (Table 8) occurred mainly from the leaves, and to a lesser extent, from the roots, as was the case with N [17]. Branches and buds exported very little K. K contributed 54% to 63.8% of the total exported in normal plants, and 61.8% to 79.2% in the deficient ones. Roots from adequately supplied plants contributed 30.2% to 41.0% whereas those from deficient plants contributed 20% to 33.4% of the total. It follows that deficient plants tend to re-utilize preferentially leaf K.

The average K quantity in the plant at harvest time was equivalent to 36% of the total in the well-fed plants, against 67% in the deficient ones (Table 8). In the first, K in the fruits reached 14% of the total, and in the latter it reached 34%. These figures increase markedly when one considers the K R proportion in the fruit in relation to K in the whole plant. In the plants without nutritional stress around 38% of the total K was moved into the fruit. The corresponding value for the K deficient plants was 58%. These values are higher than those corresponding to the N balance.

4.5 Detecting Nutrient Deficiency Symptoms in Coffee

The overall rate of coffee growth and production depends on the least available plant nutrient. Plants will grow and produce only as much as the least available nutrient will allow them to. It does not matter how much of the other nutrients are available to the plant because it is the least available nutrient that limits growth and development. This is well illustrated in the 'Barrel Analogy' diagram [23,25] here the barrel can hold only as much water as the shortest plank will allow (Fig. 4).

This is known as the 'Law of the Minimum' and is explained thus: The level of water in the barrel (Fig. 4) represents the level of crop yield that is restricted by the most limiting nutrient, nitrogen. When nitrogen is added, the level of crop production is controlled by the next most limiting factor (in this example, potassium). Poor nutrition is a major cause of coffee dieback. Plants lacking sufficient N (nitrogen) and K (potassium) suffer from dieback, especially where there is poor shade cover and insufficient water.

Low soil calcium and phosphorus will hinder root development and contribute to dieback. Dieback causes loss of yield and when severe, plants can die, especially high yielding, dwarf Arabica coffee varieties such as Catimor [24].

Table 8. Export of K by organs formed before flower differentiation and contribution of reserve K to the accumulation of total K at harvest [17]

Potassium exported by organs of reserve (as % of total K)					
Normal plants			Deficient plants		
Leaves	**Branches + Buds**	**Roots**	**Leaves**	**Branches + Buds**	**Roots**
58.9 (8.3)	5.5 (54.0)	35.6 (15.1)	70.5 (12.3)	2.8 (58.9)	26.7 (25.1)
Utilization (%) of K from organs of reserve by organs formed before and after differentiation of flower buds					
Normal Plants			**Deficient Plants**		
Anterior flush		**Posterior flush**	**Anterior flush**		**Posterior flush**
Leaves			**Leaves**		
47.0 (11.0)*		32.3 (16.4)	65.1 (16.5)		60.5 (13.0)
Branches			**Branches**		
41.4 (20.8)		29.6 (12.0)	60.4 (14.9)		74.0 (16.3)
Roots			**Roots**		
	38.6 (15.2)			72.6 (8.3)	
Fruits			**Fruits**		
	42.9 (6.7)			73.6 (10.7)	

Numbers between parentheses correspond to coefficient of variation (%)

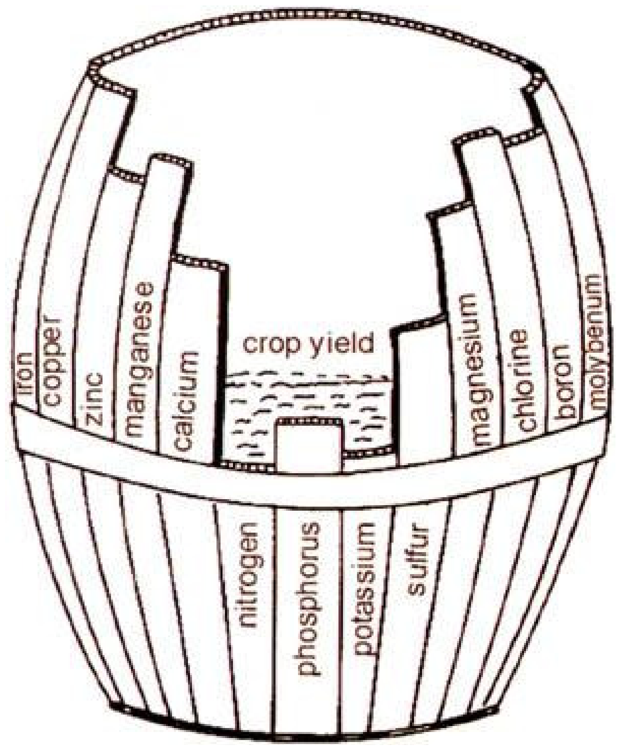

Fig. 4. 'Barrel Analogy' using nitrogen as the least available nutrient [23]

5. RECENT TRENDS IN COFFEE NUTRIENT MANAGEMENT

Coffee is produced essentially in the East African countries (Ethiopia, Kenya and Uganda) mainly by smallholder farmers with few resources to allocate to soil improvement [31]. Moreover, because of the high population density, especially in Ethiopian highlands, farmers are faced with rapid soil fertility decline as a result of continuous cropping and inappropriate cropping systems with very little or no external nutrient input to replenish soil fertility [5]. Therefore, coffee yield is generally low in most regions and is most likely to decline because of the ever increasing population density and poor traditional practices exercised in maintaining soil fertility.

In East African coffee growing regions, low soil fertility is the most important yield-limiting factor [31,32]. The major soil fertility related problems are found to be low available phosphorus (P) and nitrogen (N), and soil acidity, which is associated aluminum (Al) and manganese (Mn) toxicity. According to the Atlas of coffee production in Africa [31] P is deficient in 65 to 80% of soils and N in 60% of soils in coffee production areas of East Africa, while about 45 to 50% of soils are acidic with a pH less than 5.2, containing high levels of either Al or Mn.

Several technologies have been developed through collaborative research efforts in Ruiru, *(Coffee Research Foundation in Kenya)* to develop the strategies and technologies that enhance resilience to environmental stresses and improve coffee productivity and product quality [32]. These include: (i) development of diagnostic tools for soil fertility assessment that are adapted to local conditions; (ii) replenishing soil nutrient pools, maximizing on-farm recycling of nutrients, and reducing nutrient losses to the environment; and (iii) improving the efficiency of external inputs (Fig. 5). This strategies mainly focus on Integrated Soil Fertility Management (ISFM) is therefore, an approach that stresses sustainable and cost-effective management of soil fertility [33]. The strategy (Fig. 5) also relies on a holistic approach that embraces the full range of driving factors and consequences of soil degradation- biological, chemical, physical, social, economic, health, nutrition and political [32]. ISFM attempts to make the best use of inherent soil nutrient stocks, locally available soil amendment resources and mineral fertilizers to increase land productivity while maintaining or enhancing soil fertility. As indicated in ISFM [33]

'A set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity. A conceptual diagram is shown in figure below.

5.1 Nutrient Management for Organic Coffee

Coffee cultivated and processed in a sustainable and viable agro-ecosystem without using any synthetic chemicals is generally referred to as organic coffee [34]. Further, it has to be certified to claim as organic. Organic coffee is being produced by about 20 countries in the world such as Bolivia, Brazil, Cameroon, Costa Rica, Colombia, Dominican Republic, East Timor, EL Salvador, Ethiopia, Guatemala, India, Indonesia, Madagascar, Mexico, Nicaragua, Papua New Guinea, Peru, Tanzania, Uganda and Vietnam, with the major production share coming from Mexico, Nicaragua, Brazil and Papua New Guinea. Recently many countries like India, Kenya, Uganda etc., have taken major initiatives in promoting organic coffee production for exports [35].

Mexico is the largest producer of organic coffee in the world with one-thirds of its total production being certified as organic. In this country, majority of organic coffee is grown by small holder groups. The largest groups have around 5000 members. It is roughly estimated that some 100,000 coffee producers are involved in organic coffee production [34].

Although, reported that organic coffees are in dynamic continuum and can be perceived as an ongoing process rather than a static achievement in the export market [35]. These coffees not only provide direct economic benefit through premium price but also provide additional superior benefits that help producers improve their sustainability by providing distinct environment and social advantage at the producer level in the field. The business for these coffees has recently grown quite robust at all levels of the supply chain because of human health reasons and environmental safety.

In Ethiopia, establishing new coffee plantations under organic production system require special attention to a certain aspects of cultivation practices [36]. These include **c**hoice of varieties that must be well adapted to local conditions that are tolerant/ resistant to pests/diseases, use of organic manures and appropriate shade trees. Also, seeds for raising nursery should be collected from organic estates/ blocks only. However, if not available, seeds from conventional estates/ blocks not treated with any chemicals can be used. In newly planted fields, green manure crops like cow pea and other leguminous crops could be cultivated for two or three years to build up soil fertility and so as to prevent competition for soil moisture. Also, the following practices would be essential for meeting the nutrient requirement of young coffee holdings**:** (i) **c**orrection of soil pH using agricultural lime or dolomite, based on soil test values, at least once in 2-3 years, (ii) application of farmyard manure or compost prepared on the farm @ 500 kg/acre per year, (iii) deficiency in nutrient supply can be met by using other permitted products like rock phosphate, bone meal, wood ash etc., and (iv) use of bio-fertilizers may also be resorted to, in a restricted manner, to improve nutrient use efficiency.

Most of Ethiopia's coffee at present is grown organically; that is, without the use of pesticides (though fertilizers and even an occasional fungicide are applied to coffee trees). In addition, there are no enzymes used in the washing stations or in the fertilization process. The government is trying to obtain formal designation for its organic coffee in the hopes that this will improve the marketing potential and prices for Ethiopia's coffee, particularly in the west where organic products are highly desired [3]. The forest and semi-forest (10%), garden coffee (85%), and plantation coffee (5%) are the major conventional production systems. There are variations in genotypes, eco-physiology and the biosphere of coffee under different production systems in Ethiopia. Plantation coffee can be regarded as an intensively technified system. The small scale farmers are the major producers, whereby about 140 local coffee land races known to grow as garden with owing on average 0.5 ha of coffee farming systems [37].

Organic coffee production is based on the use of renewable resources and clearly aims to sustain management of natural resources (soil, biodiversity, water, nutrients, energy etc.) [34]. A survey conducted on major coffee producing regions during March 2004 in order to assess the

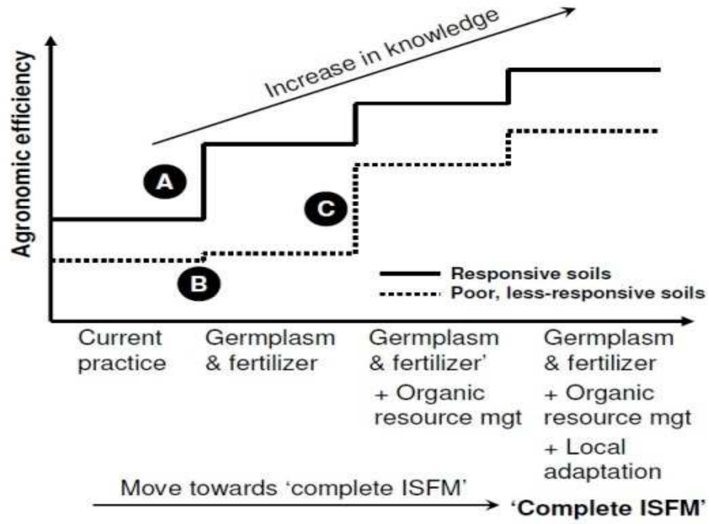

Fig. 5. Conceptual relationship between the agronomic efficiency of fertilizers and organic resource and the implementation of various components of ISFM, [33]

current status of certified organic coffee production (OCP) in Ethiopia (*in South., Sidamo, and Yirga Chefe) and South West (Jimma, Agaro and Gomma II plantations).* As was reported, that more than 90% of the coffee produced was accepted by *de facto* organic coffee [36]. The use of coffee husks/ pulps as compost to improve the soil nutrient status of coffee has been positively reported [38], and still there are several ongoing studies for present and future production regime at Jimma Agricultural Research Centre (JARC). Regular hand-picking of red cherries, washing or sun-drying of green beans are harvesting and processing methods, though there is known to be an established internal control system by the organic certifier throughout all the chains of production, processing and marketing activity.

5.2 Bio-Fertilizers for Coffee Plantation

The soil acts as a reservoir for millions of microorganisms, of which more than 85% are beneficial for plant life. Thus, the soil is a resilient ecosystem. Good soil consists of 93% mineral and 7% bio-organic substances. The bio-organic parts are 85% humus, 10% roots, and 5% edaphon [39]. Accordingly, Humus is a product of the synthetic and decomposing activities of the microflora; it exists in the dynamic state. It is under continual attack, yet it is constantly reformed by the subterranean inhabitants. Similarly, edaphon is a world of life and consists of microbes, fungi, bacteria, earthworms, micro-fauna, and macro-fauna as follows: (i) 40% fungi/algae, (ii) 40% bacteria/actinomycetes, (iii) 12% Earthworms, (iv) 5% Macrofauna, and (v) 3% micro/mesofauna. Thus, soil microorganisms provide precious life to soil systems catering to plant growth. These microorganisms work *incognito* to maintain the ecological balance by active participation in carbon, nitrogen, sulphur and phosphorous cycles in nature. Soil microorganisms play a pivotal role both in the evolution of agriculturally useful soil conditions and in stimulating plant growth [40].

Bio-fertilizers refer to living, microbial inoculants that are added to the soil. They do not pollute the environment, eco-friendly and harmless. Bio-fertilizers address the core issue of supplementing nutrients, without affecting environment and a low-cost technology for coffee growers. Most of them add nitrogen to the soil through a process called biological nitrogen fixation (BNF). On a worldwide basis it is estimated that about 175 million tons of nitrogen per year is added to soil through biological nitrogen fixation (BNF). These bio-fertilizers are products consisting of selected and beneficial microorganisms, which are known to improve plant growth through supply of plant nutrients [41]. The soil microorganisms used in bio-fertilizers are: Phosphate Solubilizing microbes, Mycorrhizae, Azospirillum, Azotobacter, Rhizobium, Sesbania, Blue Green Algae, and Azolla [42,43].

6. ROLE OF SHADE TREES IN ASSISTING SOIL NUTRIENT STATUS OF COFFEE

Interest in shade-grown coffee is now increasing because of declining coffee prices in the world market and an increasing trend toward "green consumption (organic coffee). Traditionally, coffee has been cultivated under a shade cover, but the development of new, sun-tolerant, high-yielding coffee varieties during the 1950s and 1960s led to the conversion of many traditional shaded systems to un-shaded systems. In many coffee growing countries where over millions ha are planted with coffee, it is estimated that almost more than half were converted to modern, shade-less production by 1990 [44]. However, negative effects associated with such modernized plantations have come to light over the past two decades, such as increased soil erosion, loss of biodiversity, and high environmental and economic costs associated with the heavy use of fertilizers and pesticides required in these systems [45].

With the recent decline in world coffee prices and an increase in demand for organic coffee, the role of shade trees in coffee production is receiving renewed attention as "Shade-Grown" or organic, is a promising option for farmers, as the coffee can be sold at a premium price. Although, modern coffee varieties can obtain higher yields when grown under full sun in optimal environmental conditions is still dominant in volume of production worldwide [45]. Accordingly, the impact of the loss of biodiversity due to the conversion of shaded coffee systems to non-shaded systems has been the focus of numerous studies published during the 1990s. This conversion is alarming, as there is increasing species diversity (plants, arthropods, birds, and mammals) along the continuum from coffee as a monoculture to the most traditional indigenous coffee plantations [44].

7. SUMMARY AND CONCLUSION

Several technologies have been developed and widely tested with successful results, resulting in development of soil fertility management for coffee plantations in Ethiopia. The use of inorganic and organic sources have been developed for different coffee growing agro-ecologies based on the production systems , but, coffee farming conditions in Ethiopia are worsened by declining soil fertility as a consequence of population pressure on a limited land base. Recent research findings in coffee nutrient management have made substantial contribution for numerous smallholder coffee farming communities and private sector coffee growers, but, technologies generated in using mineral fertilizers and other soil fertility management options are fairly contributed to the productivity of coffee plant due to ecological dynamism and weak adoption of technologies by the majority of coffee growers (smallholding farmers). It still demands the maximum effort of researchers, extension workers, and farmers (coffee growers) for assessing and implementing options of using scarce resources for maintaining soil fertility and improving coffee yields in different cropping systems. Also, identification and use of cultivars with improved performance on low fertility soils need to be developed and made it possible to improve coffee production.

Coffee growers in Ethiopia still demands for mitigation to obtain various technologies and services from appropriate partners *(Government, Research Institutes (regional or National). and NGOs)* for maintaining soil fertility. Various locally available resources such as lime and organic resources alone or in combination with mineral fertilizers has to be used in improving nutrient use efficiency and productivity of coffee plant. Maximal use of locally available nutrients through low-external input technologies and techniques, combined with optimal use of external nutrients appears to be the best option to boast coffee production and productivity. Integrated nutrient management will be another area of focus whereby different plant nutrient sources (organic or inorganic) will be investigated with appropriate ratios in order to reduce costs for commercial fertilizers and sustain productivity through balanced fertilization. In addition to the current endeavors in the field, more research activities are still required to address the tangible concerns regarding soil erosion. Hence, action oriented research activities are to be devised in the areas of inorganic fertilizer management, integrated nutrient management, and soil erosion control to manage nutrient and soil P^H status in the suitable range for coffee cultivation.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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