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Original Paper

Calculating Soil Nutrient Depeletion of Smallholder Farms in Northern Ethiopia Using Full Soil Nutrient Balance

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Abstract— **Soil fertility is the controlling factor of agricultural production worldwide including Waghimera zone, Ethiopia. However, it has been diminished from time to time and leads to low crop yield. Measuring of soil nutrient inflow-outflow affords necessary information about the current nutrient status of the soils, and to take appropriate nutrient management practices. The study was conducted to estimate the full soil nutrient balance of cultivated farms in the northern, of Ethiopia, in the 2020/21 main season. Inflow and Outflow of N, P, and K into, and out of farms were measured through the interview, field measurement, laboratory analysis, USLE model, and pedo-transfer functions. The full N balance of barley, tef, and wheat were -66.7, -8.9, and -47.1 kg ha^{-1} yr^{-1}, respectively. P full balance was -5.4, 1.4, and -1.9 kg ha^{-1} yr^{-1} for barley, tef, and wheat farms, respectively. Whereas, K balance was also -12.4, -3.3, and -6 kg ha^{-1} yr^{-1} for barley, tef, a nd wheat, respectively. The balance quantification was done by subtracting nutrient outflows from the inflows. The results revealed that N, P, and K had negative balances except for P in tef. Grain yield and crop residue removal were the major paths of nutrient loss. To sustain, and boost agricultural production, reversing the imbalance between inflows, and outflows is critically essential for the study area. The current highly depleted nutrient should be corrected by adding sufficient organic, and inorganic nutrient sources, like in situ manuring, biochar, green manure, and remaining crop residue in the fields.**

***Keywords*— balance, cultivated farm, inflow, outflow, soil nutrient**

I. INTRODUCTION

Soil fertility is one of the main biophysical challenging factors for the agricultural production of cultivated farms [1]. However, it has been diminishing due to an imbalance of soil nutrient dynamics via poor farm management of low input addition and soil erosion [2-4]. Also, frequent nutrient removal without substituting by above-ground biomass depletes soil fertility [5]. Then soil fertility deterioration affects agricultural productivity, food security, and sustainability [6-8]. Thus, soil fertility management needs great attention within different stakeholders of agricultural sectors, because it controls crop production and productivity [9]. Moreover, soil fertility status varies based on agroecology, soil type, wealth status, and awareness of the society spatially and temporally [10]. So, to sustain the agricultural productivity of cultivated farms immediate and proper corrective measures should be done on time in place [11].

Quantifying soil nutrient inflow-outflow dynamics at the cultivated farm level is an essential tool for taking appropriate management measures [12]. Soil nutrient balance is the summation difference between inflows and outflows fluxes of nutrients within a particular framework over a certain period [13]. It is used to assess the existing fertility status of agricultural cultivated fields, nutrient depletion rate, sustainability of farmland, and soil fertility management practice [14-17]. Many studies conducted on cultivated farms in different parts of Ethiopia showed that the outflows of NPK nutrients are greater than the inflows [18-19]. Ethiopian soil nutrient balance results showed negative values, due to poor soil fertility management practices, and low organic and inorganic nutrient source addition [20-22].

In the study area, the existing practice of soil fertility management is underprivileged, hence agricultural production and productivity are low. The action of crop residue management on the farms is low for competitive use to animal feed, and energy sources. Consequently, there has been food insecurity and continuous refuge [23]. This study was proposed to quantify nitrogen, phosphorous, and potassium inflows-outflows (full soil nutrient balance) of cultivated farms in the Sekota district in northern Ethiopia. Primarily to assess the present trend of soil nutrient dynamics of the farmlands, and to block and reverse the increasingly severe soil fertility decline scenarios. The generated nutrient balance result is used as input for decision-makers to plan and implement integrated nutrient management strategies on the farmlands.

II. Materials and Methods

A. Description of the Study Area

The study was conducted at the Agew Mariam watershed located in Sekota woreda Wag-himra zone, Amhara national regional state, Ethiopia. The inflow-outflow of nutrients at cultivated farms was measured in the 2020/21 main cropping season. As shown (Figure 1), it is located from 38^0 53’14’’to 38^0 56’15’’ longitude and 12^0 31’40’’ to 12^0 32’ 33’’ latitude with an altitude of 2104 to 2361 m. a. s. l. The rainfall pattern is uni-modal, with rains from the end of June to early September. The area has mean annual rainfall was 590 mm, while the mean annual minimum and maximum temperatures were 13 °C and 27 °C, respectively from 2000-2020 years (Kombolcha Metrological Station). According to [24], the area is grouped under semi-arid midland. The soil types are Nitisols, Vertisols, eutric Regosols, and eutric Cambisols [4] (Esubalew *et al*., 2023). The major land-use types are cultivated (71.4 %), bushland (19.7%), area closure (8.2%), and residence (0.7%) [25]. The farming system is characterized by subsistence mixed crop production and livestock husbandry. The main grown crops are bread wheat (*Triticum aestivum L.),* sorghum (*Sorghum bicolor L.),* tef *(Eragrostis tef (Zucc.*) Trotter), barley (*Hordeum vulgar L*), and faba bean (*Vicia faba L*.). The dominant livestock productions are cattle, apiculture, poultry, goat, sheep, and donkey.

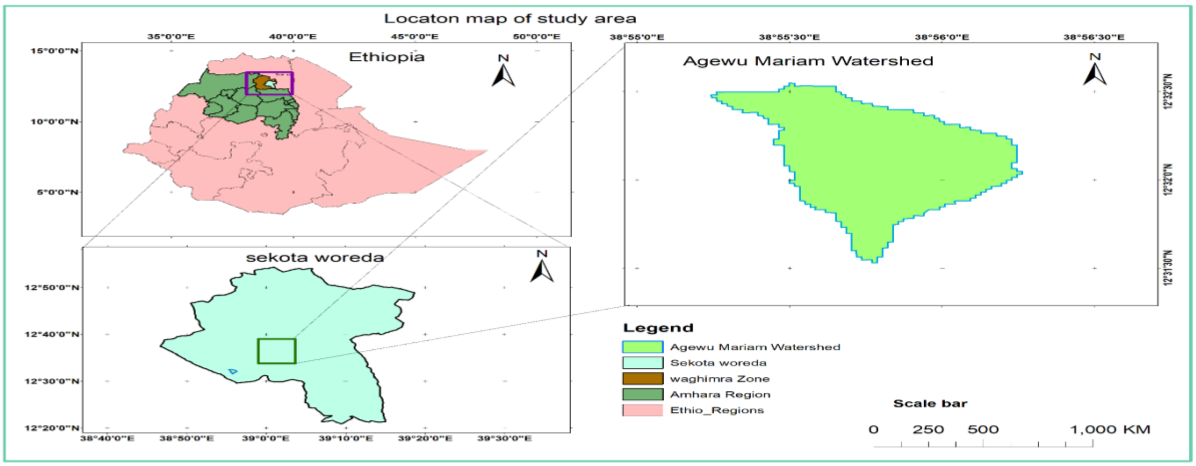

Fig.1. Location Map of The Study Area

B. Data Collection and Analysis Methods

The sample data were collected in a purposive random sampling technique including different slope class levels, socio-economic status, soil fertility level, and management activities. Totally 23 representative cultivated farms were selected, among them 10 wheat, 3 barley, and 10 tef, farmer’s farms used as a replication. The inflows of N, P, and K through mineral fertilizer and organic fertilizers were estimated by reviewing the sampled site's owner. Furthermore, the inflows of N, P, and K through atmospheric deposition were estimated using the [26] model:

$$IN3\ N = 0.14P^{1/2}$$

$$IN3\ P = 0.023P^{1/2}$$

$$IN3\ K = 0.092P^{1/2}$$

Where P is the annual rainfall (mm yr^{-1}).

Even though the sampled crops were cereals, according to [27-28] non-symbiotic N-fixing plants fulfill their 40% nitrogen requirement naturally. Based on this the inflow of N from biological nitrogen fixation was estimated by pedo-transfer functions using a reassign equation [29].

$$IN4= 0.5+0.1P^{1/2}$$

Where P is the annual rainfall (in mm).

However, in the study area producing crops using irrigation was yet not practiced, and there was no deposition of eroded soil from other areas. Consequently, there were no inflows of NPK from irrigation water and deposited soil. Simultaneously, the outflows through harvest crop yield and residue removal were quantified by multiplying the amount of grain and straw by its nutrient contents [29] formula. The amount of above-ground biomass (grain, and straw) was collected directly from the entire field using a hanging balance. Moreover, the N, P, and K contents of the crops were analyzed in the laboratory based on their standard procedures. The outflows of N, and K through leaching were quantified using the transfer functions. While P is not leached since it is highly bounding with soil particles [30]. The outflow of N and K via leaching (OUT3) was calculated using [13] model.

$$OUT3N = 2.3+ (0.0021 + 0.0007 * F) * P+0.3 * IN1+IN2-0.1 * TNU$$

$$OUTK3 = (0.6+ (0.0011 + 0.002 * F) * P+0.5 * (IN1+IN2)-0.1* TKU)/1.2$$

Based on [31], TNU and TKU (kg ha^{-1}) = nutrient content % X yield (kg ha^{-1}) /100. Where, p: annual rainfall, F: soil fertility class (1= low; 2 = moderate; 3 = high), IN1+IN2: mineral fertilizer and manure applied (kg ha^{-1} yr^{-1}) and TNU, TKU: total N and K uptake (kg ha^{-1} yr^{-1}), respectively.

Gaseous loss (OUT4) of nitrogen in denitrification and volatilization form from agricultural fields was estimated based on the model developed by [13].

OUT4 = (0.025+0.000855*P + (0.01725*(IN1+IN2) + 0.117)) + (0.113 * IN1+IN2)

Where, p = annual rainfall; IN1 + IN2: mineral fertilizer and manure applied (kg ha^{-1} yr^{-1}), respectively.

The loss of soil via soil erosion was estimated using the universal soil loss equation (USLE) model [32] with A= R * K * LS * C * P

Based on [33] quation NPK loss through soil erosion (OUT5) (kg $ha^{-1}yr^{-1}$) = soil loss (kg ha^{-1} yr^{-1}) X NPK content of the soil (%) X field size (ha)

Finally, nutrient balances were quantified by subtracting the summation of outflows from the summation of inflows [13]. Field surveyed, laboratory analyzed soil and plant samples data of inflows, and outflows were summarized using Microsoft Excel spreadsheets, and additionally, statistical analysis was done using SAS software version 9.0, and the mean separation was analyzed by using 0.05 probability level of least significance difference (LSD). One kilogram composite soil sample was collected from ten subsamples by using an augur at a depth of 0.2 m for the analysis of N, P, and K contents, soil SOC, and soil separate particles. The inflows of NP from the added NPSZnB and urea fertilizers were converted into corresponding total N and P in kg ha^{-1} by multiplying the amount of P_2O_5 by 0.44. Similarly, the total quantity of applied NPSZnB and commercial urea fertilizer was changed into elemental nitrogen amount [21]

C. Soil sample analysis

The soil samples were analyzed at Sekota Dryland Agricultural Research Center and Amhara Design and Supervision Works Enterprise soil laboratory (ADSWE). The soil was air-dried and sieved through a 2 mm sieve for NPK and textural class analysis, and some samples were sieved at 0.05 mm for SOC analysis. Soil organic carbon was determined following the wet digestion method [34], total nitrogen was determined by the Kjeldahl method [35]. Available potassium determined by Morgan’s solution and K in the extract was measured by a flame photometer [36]. Available phosphorus was determined following the Olsen method [37], and soil texture was analyzed through the hydrometer method [38].

D. Plant sample analysis

The plants were harvested manually at their maturity dates preferred by the farmers. Crop biomasses were weighed using a hanging balance. Similarly, the grain yield of barley, tef, and wheat was measured at threshing time. Representative straw samples were taken to oven-dry and dried at 65^0 C for 72 hours to avoid moisture content. Then both straw and grain were air-dried and grinded to pass through a 0.15 mm mesh [39]. The concentrations of the total nitrogen in the plant were determined by micro-Kjeldahl digestion, distillation, and titration methods [40]. Phosphorous and potassium concentrations in the plant were measured by spectrophotometer and flame photometry, respectively, and determined with the procedure described by [41].

III. Results And Discussion

A. Inflow of NPK Nutrients

The inflows of NPK for the major grown crops of barley, tef, and wheat through organic and inorganic fertilizer sources were very low. Farmers respond in interviews a few of them (30.4%) use inorganic fertilizers for the production of tef, barley, and wheat. They applied synthetic fertilizers in the form of NPSZnB and urea for the production of field crops. The average added nutrient for the barley was 7.7 kg N $ha^{-1}yr^{-1}$ but no addition of P fertilizer sources. For tef 5.1 and 2.6 kg ha^{-1} yr^{-1} N and P were used, respectively. While in wheat farmlands 3.1 and 2.7 kg ha^{-1} yr^{-1} N, and P were added, respectively. It is indisputable proper soil nutrient management is a key factor in increasing crop production and sustaining soil productivity [42]. However, there was no K sources fertilizer addition was done for each study crop farmlands. The added N and P amount was very low and could not meet the crops' optimum requirement of nutrients for better production. The recommended amount of nitrogen and phosphorous for tef and wheat in the area was 92 and 10 kg ha^{-1} N and P, respectively [43-44]. However, the crops in the study area had no responses to K on crop yields [45]. However, this statement disagrees with the findings of [46] in Chencha and Hagere Selam in Southern Ethiopia K had responses on wheat yield.

The amount of nutrient inflow addition in the study area was low, this was not only to the study area but also to other areas [47-48]. This was due to the poor habit of farmers to use mineral fertilizers for field crop production. Most of the farmers were poor and, as a result, could not afford the money to purchase and use mineral fertilizers for their farms. The reasons were high poverty levels, lack of reliable credit services, and the ever-increasing cost of mineral fertilizer that affected farmers’ fertilizer usage. According to [20,49], the above-mentioned reasons were enforcing Ethiopian farmers to add low inputs in their farmlands. Generally, in Ethiopia, the smallholder farms' fertilizer probability is 30–40% [50]. As a result, the production of cereal crops yield was low [51]. In addition, unreliable, and erratic rainfall is another factor because in dryland areas these fertilizers negatively affect crop production [52]. This study's results are in line with [6,53] who reported that poor farmers purchase lower amounts of chemical fertilizers compared with the rich.

This study ratified in the interview, that farmers did not apply organic fertilizers (farmyard manure and compost) to their barley, tef, and wheat farms. Due to the low number of animals per household for the production of excess farmyard manure. The smaller amount of farmyard manure produced per household is mostly used in backyard plots and as fuelwood. So, there were no inflows of N, P, and K from organic sources to the major cereal field crops. The availability of organic sources' of fertilizers depends on livestock number and family labor size for transporting to the farmlands [20]. However, currently, in the study area as well as in the rest of the country, farmyard manure is used as a source of energy [54].

The inflow addition of N, P, and K by atmospheric deposition was calculated by using rainfall data of the season 830 mm. Based on this barley, tef, and wheat farmlands received the same amount of N, P, and K (4.03, 0.66, and 2.65) kg ha^{-1} yr^{-1}, respectively. Barley, tef, and wheat are not leguminous crops, but all of these crops benefited from non-symbiotic nitrogen fixation associations [28] (Santi *et al.*, 2013). The value of nitrogen added to barley, tef, and wheat farms was the same 3.38 kg ha^{-1} yr^{-1}. This value was similar to the [47] results of tef and wheat farms that received 4 kg N ha^{-1} yr^{-1}. The total inflows of barley were 15.08, 0.66, and 2.65, for tef 12.47, 3.24, and 2.65, and for wheat 10.52, 3.39, and 2.65 kg ha^{-1} N, P, and K, respectively (Table 3). The major sources of inflows were mineral fertilizer, atmospheric deposition, and non-symbiotic nitrogen fixation to N. However, the overall inflows were very low and shocking. The inflow amounts of N and P were not equivalent to the recommended.

TABLE 1. NUTRIENT INFLOWS INTO THE FARMLANDS OF SELECTED CROP TYPES

Crop fields	**IN1**			**IN2**			**IN3**			**IN4**
	N	**P**	**K**	**N**	**P**	**K**	**N**	**P**	**K**	**N**
Barley	7.7	0	0	0	0	0	4.03	0.66	2.65	3.38
Tef	5.1	2.6	0	0	0	0	4.03	0.66	2.65	3.38
Wheat	3.1	2.7	0	0	0	0	4.03	0.66	2.65	3.38

Where IN1 refers to inflows of NPK from inorganic sources, IN2 refers to inflows of NPK from organic sources, While, IN3, refers to inflows from atmospheric deposition, and IN4 refers to inflows of N via non-symbiotic N fixation.

B. *Outflows of NPK Nutrients*

The outflows of nitrogen, phosphorous, and potassium via harvested crop yield to barley were 40.1, 3.8, and 3.1, from tef 6.2, 0.6, and 0.6, from wheat 22.5, 2.4, and 1.3 kg ha^{-1} yr^{-1}, respectively (Table 2). The magnitude differs among crop types due to their production yield, and nutrient uptake [55-57]. The outflows of N, P, and K by crop residue removal from barley were 33.6, 2.2, and 9.2, from tef 8.7, 1.2, and 2.6, and wheat 31.3, 2.9, and 4.1 kg ha^{-1} yr^{-1}, respectively. The loss of K through straw residue removal is greater than grain yield because straws had a high K content [58-59]. Whereas, the straw of cereal crops had lower N and P contents than grain yield [45,57]. The outflows of N and K via leaching were 5.3 and 3.1 for barley, 4.7 and 3 for teff, and 1.5 and 2.3 for wheat kg ha-1 yr^{-1}, respectively. Nitrogen outflows by gaseous losses in volatilization and denitrification were 1.9, 1.5, and 1.3 kg ha^{-1} yr^{-1} for barley, tef, and wheat, respectively. The outflows of N through soil erosion were 0.9, 0.3, and 1 kg ha^{-1} yr^{-1} for barley, tef, and wheat, respectively. The loss of P from barley, tef, and wheat were 0.02, 0.01, and 0.03 kg ha^{-1} yr^{-1}, respectively. Whereas, 0.6, 0.2, and 0.74 kg K ha^{-1} yr^{-1} were outflowed from barley, tef, and wheat farms, respectively. The differences were due to differences in slope steepness and length, soil erodibility factor, management practice, and nutrient contents of the soil [60-61]. The outflow result of NPK by soil erosion in this study was similar to the findings of [62] who reported that 2.36, 0.018, and 0.32 kg ha^{-1} N, available P, and exchangeable K were lost, respectively.

The total N outflows from barley, tef, and wheat fields were 81.8, 21.4, and 57.6 kg ha^{-1} yr^{-1}, respectively. P outflows from barley, tef, and wheat farmlands were 5.02, 1.81, and 5.33 kg ha^{-1} yr^{-1}, respectively. The total removal of K from barley, tef, and wheat farms were 5.1, 5.2, and 7.4 kg ha^{-1} yr^{-1}, respectively. The major paths of NPK outflows in each crop farm were harvested crop yield, crop residue removal, and leaching. The variation in magnitude among crop farms was due to variations in grain and straw yield, slope length, slope steepness, soil erodibility, and nutrient uptake [63-64]. Thus the implementation of soil and water conservation structures played an important role in minimizing nutrient loss by soil erosion. Besides this, the rainfall's effect on the loss of nutrients was low, because its amount was small [65-66].

C. *Full soil NPK nutrients balance*

The analysis of the result showed that barely farmlands had -66.7, -5.4, and -2.5 kg ha-1 yr-1 N, P, and K balance, respectively. Tef farms -8.9, 1.4, and -2.6, as well as wheat farms -47.1, -1.9, and -4.8 kg ha-1 yr-1 N, P, and K balance, respectively. The nitrogen balance of major crop-type farms had a negative balance. It showed that there was an imbalance between inflows and outflows. The amount of exited N from the soil was higher than the added. This implies that N was highly depleted from the farming system. N balances of barley < wheat < tef, this was related to its yield levels, and inflow of inorganic nutrient sources. As a result, nutrient depletion increased with yield levels [48]. According to [67-68] the level of N outflows is grouped under the category of high for teff and very high for barley and wheat farms. Nitrogen highly depleted due to continuous cultivation without adequate inflow supplies, poor land management, and low addition of nutrient sources [69]. This threat is common in Ethiopian soil including large areas of sub-Saharan Africa [13,70]. Diminishing of N regulating the sustainability of agricultural production [71]. This study's finding results had similar trends with most nutrient balance studies carried out in Ethiopia, all of them had negative N balance values [47-48].

Phosphorous balance of barley and wheat farms were negative, whereas, tef had positive values, the outflows were higher than inflows (Table 3). Balance of tef > wheat > barley farmlands, as a result of no P inflows addition for barley farmlands. The status of P lost was classified under moderate for tef and high for wheat and barley farms [67-68]. Outflow of P by grain harvested crop and residue removal contributed the highest role of becoming negative P balance [19]. Negative P balances showed that it was depleted and soil fertility had declined. Phosphorus is a unique agricultural input because global supplies of phosphorus are limited by known phosphate reserves and geological time scales [72]. The overall P balance is better than the N balance since P removal via leaching and denitrification losses are negligible [73]. This study result had nearly similar value to most P balance studies, and most of them showed positive values [16,20-21,48].

Potassium balance of the major dominant crop farms was negative (Table 3), due to imbalance inflows and outflows. The only K nutrient inflow source was atmospheric deposition, there was no organic, and mineral nutrient sources added to the soil. However, the outflows paths were grain yield, straw removal, leaching, and soil erosion, as a result, the balance was not proportional. Though, the depletion level of K was categorized under low [68]. The major paths of K outflow were leaching and straw residue removal. The reasons were, straws had high K content and its characteristics of easily leached [74]. K status in the soil has declined and the situation will not be reversed, the soil will become incapable of producing crops. Therefore, sources of K should be added to the soil like put crop residue in the field, using compost and mineral nutrient sources [75-76]. This study result had a nearly similar numerical value with [16,19-20,47-48] findings. Almost all of the K balance studies in Ethiopia showed that negative balance, due to low inflow addition, and high outflows.

TABLE II. THE AMOUNT OF NUTRIENT OUTFLOWS FROM MAJOR FARMLANDS (KG HA^{-1} YR^{-1})

	OUT1			**OUT2**			**OUT3**		**OUT4**	**OUT5**		
Crop	**N**	**P**	**K**	**N**	**P**	**K**	**N**	**K**	**N**	**N**	**P**	**K**
Barley	40±30	3.8±1.8	0.5±0.3	33.6±22	2.2±0.3	0.9±0.4	5.3±3.8	3.1±0.1	1.9±1.7	0.9±0.8	0.02±0.01	0.6±1
Tef	6.2±2	0.6±0.2	0.6±0.3	8.7±2.7	1.2±0.2	1.4±0.8	4.7±2.3	3±0.1	1.5±1.2	0.3±0.2	0.01±0.02	0.2±0.1
Wheat	22.5±7.7	2.4±0.7	1.6±0.4	31.3±11	2.9±0.9	2.7±0.8	1.5±0.1	2.3±0.1	1.3±0.7	1±1.4	0.03±0.01	0.74±0.9

Where OUT1 refers outflows of NPK through harvest crop yield,
OUT2 refers the outflows of NPK through crop residue removal,
OUT3 refers the outflows of NK through leaching,
OUT4 refers the outflows of N through gaseous loss in the form of denitrification and volatilization,
OUT5 refers to the outflows of NPK through soil erosion,

TABLE III. FULL SOIL NUTRIENT BALANCE OF MAJOR CROP TYPES

	Total inflows kg ha^{-1} yr^{-1}			**Total outflows kg ha^{-1} yr^{-1}**			**Balance kg ha^{-1} yr^{-1}**		
Crops' farm	***N***	***P***	***K***	***N***	***P***	***K***	***N***	***P***	***K***
Barley	15.1	0.7	2.7	81.8	6.0	15.5	-66.7	-5.4	-12.4
Tef	12.5	3.2	2.7	21.4	1.8	6	-8.9	1.4	-3.3
Wheat	10.5	3.4	2.7	57.6	5.3	8.7	-47.1	-1.9	-6

IV. CONCLUSIONS

The result of this study revealed that the balance of N, P, and K was negative in all farmlands of barley, tef, and wheat, except the tef P balance. It indicates the inflows of nitrogen, phosphorous and potassium were lower than the outflows. Consequently, the soil fertility level of Sekota district Agew mariam watershed farmlands has been mined and declined. Soil fertility maintenance and improvement management activities were poor to the expected tasks that had to be done. The practice of preparing and using compost, farm-yard manure, crop residue management, and intercropping cereals with legumes was underprivileged. Therefore, reversing the current trend of soil fertility depletion and agricultural production reduction has to be corrected in a short period. This bottleneck for crop production increment and ensuring food security should be amended by adding sufficient organic and inorganic nutrient sources. Besides, crop residue retention in the farms, planting legume crops, crop rotation, and intercropping activities should be practiced. Similarly, more extension services on the addition of organic and synthetic fertilizers shall be in place. Further studies on integrated soil fertility management activities should be practiced to recover the agricultural productivity of the farmlands.

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