Mineral Composition of Leaves and Tubers of Potato (*Solanum tuberosum* L.) Plants Cultivated in the Eastern Highlands of Ethiopia

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Abstract: The problem of low yield and quality of potato in Ethiopia is attributable to nutrient deficiencies. Therefore, a survey was conducted to elucidate the problem through plant tissue analyses. Mature and fully expanded potato leaves and tubers were sampled randomly from purposively selected smallholder potato farms across seven villages in the eastern highlands of the country. The leaves were analysed for both macro- and micronutrients and the tubers were analysed for selected macronutrients. The data were subjected to analysis of variance, and explored with descriptive statistics. Ranges of leaf and tuber mineral concentrations were compared with deficiency, sufficiency, and excess ranges published for the crop. Leaf and tuber concentrations of the selected macronutrients were subjected to a correlation analysis. The results revealed that leaves sampled from four out of seven villages were deficient in nitrogen and phosphorus. Leaves from all villages were sufficient in all other macronutrients. Similarly, tubers sampled from five out of seven villages and those from three out of seven villages were deficient in nitrogen and phosphorus, respectively. Tubers from all villages were sufficient in potassium, calcium, and magnesium. Leaf micronutrient deficiencies were detected only for iron and manganese in two villages. Leaf and tuber concentrations of most mineral nutrients varied significantly across the villages, and some correlated positively. In conclusion, potato plants in the surveyed farms suffered mainly from nitrogen and phosphorus deficiencies, followed by deficiencies of iron and manganese.

Keywords: Deficiency; Leaves; Nutrient Concentration; Sufficiency; Tubers

1. Introduction

Potato (*Solanum tuberosum* L.) is an important food security and cash crop in Ethiopia (Gildemacher *et al*., 2009). With increasing urbanization, the use of the crop not only as fresh tubers but also as processed products such as French fries and crisps is rising in the country (Abebe *et al*., 2010; Haverkort *et al*., 2012). Despite the increasing importance of the crop for household food security and income generation in Ethiopia, the national average yield ranges between 8 and 10 tons (t) hectare (ha), which is much lower than the yields obtained in the Sudan (17 t ha^{-1}) and Egypt (26 t ha^{-1}) (Haverkort *et al*., 2012). Potato provides not only carbohydrate, proteins, and vitamins but also minerals that are important in the diet for human wellbeing (Subramanian *et al*., 2011), and is important for nutritional security. It is noteworthy that potato absorbs large quantities of plant nutrients, especially nitrogen (N), potassium (K) and phosphorus (P) from the soil (White *et al*., 2007). Potassium and N are found in the largest amounts in a potato plant, followed by Calcium (Ca) and Magnesium (Mg) (Westermann, 2005). Applying fertilizers increases not only yield but also mineral concentrations in potato tubers thereby affecting the nutritional, processing and storage qualities of the crop (Harris, 1992; Rocha, 1997; Allison *et al*., 2001; Karlsson *et al.,* 2006). Consequently, it should be possible to increase tuber yield and mineral concentrations of the crop with appropriate fertilization strategies (White *et al*., 2009).

In Ethiopia, nutrient deficiencies in potatoes are very common due to either no or low application rates of fertilizers, including manure (Gildemacher *et al*., 2009; Haverkort *et al*., 2012). However, the severity of yield reductions caused by nutrient deficiencies is not as easily discerned by farmers as the one caused by drought, diseases, pests, etc. Therefore, potato farmers show less concern for soil fertility management, which is a major factor that dwarfs the yield of the crop in the country (Gildemacher *et al*., 2009). Low soil fertility management causes poor uptake and translocation of mineral elements in potato tubers (White *et al*., 2009), thereby reducing nutritional quality.

Plant tissue analysis for nutrients could be instrumental for targeting high yield (Harris, 1992). This is because tuber yield and quality in potato is strongly influenced by tissue nutrient concentrations (Beukema and van der Zaag, 1990; Harris, 1992; Maier, 1994). Plant tissue analysis could provide an effective means of elucidating plant nutritional status and help to determine whether or not a fertilizer programme is adequate to meet nutrient requirements of crops (Westermann *et al*., 1994; Rocha *et al*., 1997; Fageria, 2009). Results of such studies can help in managing nutritional status of crops during growth to achieve high yields and quality, particularly for a high cash value and intensively managed crop like potatoes (Westermann *et al*., 1994). The underlying principle of plant tissue analysis is that each crop has critical minimum nutrient concentrations below which a yield depression occurs (Prummel and Barnau-Sijthoff, 1984). Interpretation of plant analyses simply involves comparing the sample nutrient concentrations with established critical values. The critical nutrient range developed by Dow and Roberts (1982), above which crops are not expected to respond favourably to the

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addition of specific nutrients, and below which yield depressions occur, is a method widely used for interpreting nutrient concentration data.

Deficient, adequate, sufficient, high, excess or toxic concentration ranges of nutrients in several parts of the potato plant at different sampling times have been determined and described by several workers (Sharma and Arora, 1989; Bergmann, 1993; Walworth and Muniz, 1993; Gupta *et al*., 1995; Rocha *et al*., 1997). The petiole is the commonly selected plant part for use in potato nutritional analysis, although it may not be the most appropriate part of the plant for all nutrients (Walworth and Muniz, 1993). However, Reis Jr. and Monnerat *et al*. (2000) verified that analysing petioles and leaf blades together will give a better diagnosis than when these plant parts are analysed separately to evaluate the nutritional status of the potato crop. Critical leaf nutrient concentration ranges vary with regions, farming practices, levels of tuber yields, age of plants at sampling, etc (Prummel and Barnau-Sijthoff, 1984; Sharma and Arora, 1989; Walworth and Muniz, 1993; Reis Junior and Monnerat, 2000; Fageria, 2009). Relatively high critical ranges were reported for potato leaf N, P and K concentrations by Bergmann (1993) and for P and K by Prummel and Barnau-Sijthoff (1984). However, relatively moderate critical leaf concentration ranges of the three major nutrients were reported for the crop by Walworth and Muniz (1993). On the other hand, there are low variations in the critical leaf concentration ranges of Ca, Mg, sulphur (S), and micronutrients that are reported for the crop in the literature.

A review of literature showed that few studies have been done in Ethiopia to diagnose the nutritional status of potato plants through tissue analysis. The main objective of this study was, therefore, to determine and elucidate mineral nutrient concentrations in leaves and tubers of potato plants grown by smallholder farmers in eastern Ethiopia.

2. Materials and Methods

2.1. Description of the Study Areas

The survey was conducted in the month of August during the 2008/2009 main cropping season in the eastern highlands of Ethiopia. The eastern highlands of Ethiopia are located in the Hararghe Zone at 8° 50'– 9° 30' N latitude and 40° 38'–42° 20' E longitude. The altitude of the zone ranges between 1500 and 3070 meters above sea level (masl) (Table 1). The highlands experience a bimodal rainfall distribution. The small rains fall from March to April whereas the main rains fall from June to September. The average annual rainfall is 785 mm (Mulatu and Kassa, 2001). In this part of the country, smallholder farmers grow potatoes as a major food security and cash crop (Mulatu *et al*., 2006; Hirpa *et al*., 2010).

Table 1. Geographical locations of the study areas.

Village	District	Zone	Elevation (masl)	Approximate Location	
				Latitude	Longitude
Arbarakkate	Chiro	West Hararghe	2200-2500	09° 0' N	40° 54' E
Haramaya	Haramaya	East Hararghe	2000-2400	09° 23' N	42° 01' E
Hirna	Tullo	West Hararghe	1790-2300	09° 12' N	41° 06' E
Kombolcha	Kombolcha	East Hararghe	2109-2573	09° 28' N	42° 11' E
Langey	Qarsa	East Hararghe	1996-2200	09° 27' N	41° 27' E
Qarsa	Qarsa	East Hararghe	2004-2300	09° 6' N	41° 51' E
Watar	Qarsa	East Hararghe	2083-2265	09° 25' N	41° 45' E

The dominant soil types in the study areas are eutric regosols and/or eutric, dystric, vertic, calcic, chromic cambisols, and in some areas leptosols, and fluvisols are also dominant (EMA, 1981).

2.2. Selection of Study Areas

Seven villages from five major potato-growing districts in the region were targeted for the study. The districts and villages were purposively selected because farmers rank potatoes as their most important food security and cash crop (Mulatu *et al*, 2006; Hirpa *et al*., 2010). The villages included Arabarakkate and Hirna from West Hararghe Zone and Haramaya, Kombolcha, Langey, Qarsa and Watar from East Hararghe Zone, the respective districts being Chiro, Tullo, Haramaya, Kombolcha, and Qarsa (Figure 1 and Table 1). The districts selected for the survey study are situated between 09° 01' and 09° 25' N latitudes and 40° 54' and 42° 11' E longitude in the sub-humid tropical zone of the eastern highlands of the country. The altitudes of the districts range between 1790 and 2573 masl. The average minimum and maximum temperatures are 18 and 25 °C, respectively.

2.3. Experimental Procedures

2.3.1. Sampling and Sample Preparation

Ten potato farms belonging to smallholder farmers were purposively sampled from each of the seven villages in the five districts. Sixty mature, fully expanded, and healthy leaf (leaf blade + petiole) samples were randomly taken from plants in each farm. While sampling, the physiological age rather than chronological age was considered; therefore, the leaf samples were taken just before the start or initial stage of flowering (tuber initiation). Tubers were harvested at maturity from sixty randomly selected plants as done for leaf samples, from six farms in each village. The tubers were bulked and 30 of them consisting of all size categories were drawn from the harvest of each farm. There were no considerable differences in soil fertility management practices among the farmers owning the potato farms. According to information gathered from the farmers, most of the potato plantings followed maize or sorghum and the potatoes cultivated were mainly of early maturing local types. The farmers cultivating the crop reportedly applied some urea and/or diammonium phosphate (DAP) with little application of organic fertilizers except a few farmers in Arbarakkate and Kombolcha, who additionally applied some amounts of animal manure to their potato fields.

The leaves were collected and placed in paper bags and the tubers were placed in plastic buckets. All tuber samples were washed. Excess water from the leaf and tuber samples was removed by blotting up with tissue paper and the surfaces of the samples were left to dry up naturally. The tubers were minced into 3 mm slices. The leaf and 500 g sliced tuber samples were dried to constant weight in an oven at 75 °C.

2.3.2. Tissue Analysis

The dried leaf and tuber samples were ground in a Wiley mill to pass through 40-mesh of a stainless steel screen. The ground plant materials were stored in air-tight polycarbonate containers under a cool and dry condition until analysis. Both leaf and tuber tissue samples of 200 mg were drawn in duplicate for each farm for determination of mineral nutrient concentrations.

The dried leaf tissue was analysed for N, P, K, S, Mg, Ca, iron (Fe), zinc (Z), manganese (Mn), copper (Cu), boron (B) and molybdenum (Mo). The dried tuber tissue was analysed only for N, P, K, Mg, and Ca. Dried leaf and tuber samples each weighing 120 mg were scooped separately into fire-proof Pyrex glass containers and ashed overnight in a Muffle furnace at 480 °C. The ashed tissues were extracted using a 1:3 diluted nitric acid solution. The resulting solutions were filtered through Whatman filter paper and the nutrient contents in the aliquot were directly measured using inductively coupled plasma optical emission spectrophotometer (ICP-OES, Spectroflame EOP, Spectro analytical Instruments, KLVE). Nitrogen, carbon, and sulphur contents in the potato leaf samples were determined by CNS auto-analyser. For determining N concentration, 10-15 mg dried plant samples were weighed into aluminium foil and burned at the temperature of 1200 °C. For determining the sulphur concentration in the leaf tissues, dried leaf tissue samples each weighing 20 mg were scooped into aluminium foil and a similar amount of tungsten (III) oxide was added as a reaction catalyser in the presence of oxygen supply after which the samples were completely burned in the way mentioned above.

2.4. Statistical Analysis

Descriptive statistics were used to explore the data. Concentrations of mineral nutrients in the leaf and tuber tissues were compared and evaluated against the ranges reported for potato by Walworth and Muniz (1993) and Bergmann (1993). In addition, the data were subjected to one way analysis of variance (ANOVA) using GenStat, with the villages considered as treatments and the potato fields in each village as replications for survey data (Clewer and Scarisbrick, 2001). Treatment means were compared using Tukey's Studentized Range Test at 5% level of significance. Pearson correlation coefficients were determined to evaluate linear relationships between mineral nutrient concentrations in leaves and tubers.

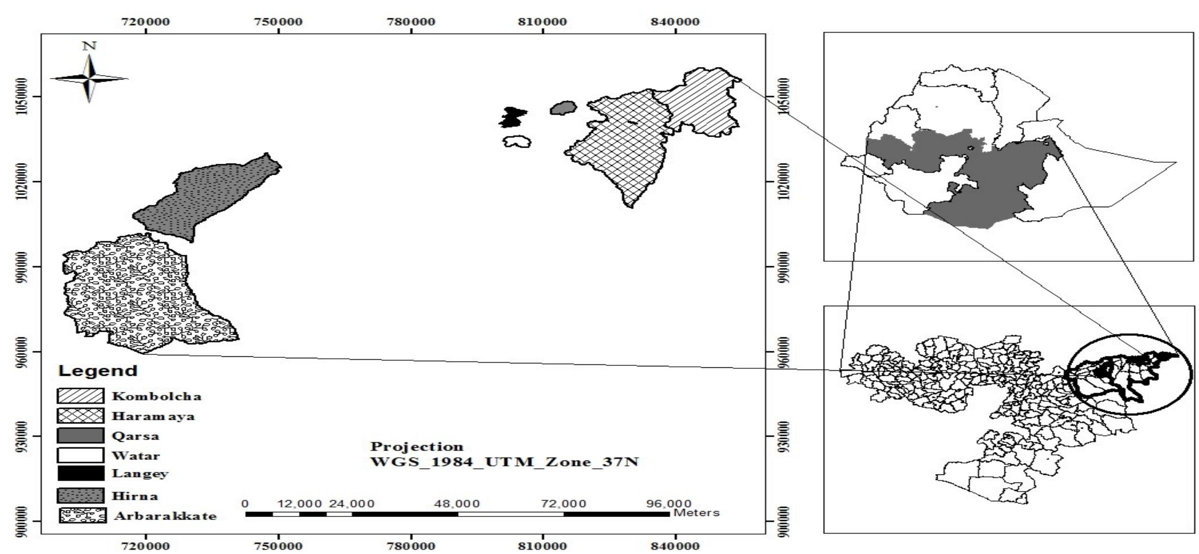

Figure 1. Map of the survey sites.

3. Results

3.1. Concentrations of Macronutrients in Leaves

Nitrogen

The concentration of N in the leaf (Table 2) varied from 23.3–50.7 mg g^{-1} leaf dry matter (2.3–5.1%). The overall mean in the leaf tissue showed adequacy in accordance with the sufficiency ranges reported for the crop in the literature. The mean values of three villages (Arbarakkate, Kombolcha, and Watar) were within the sufficiency range; however, the mean values obtained from the other four villages (Haramaya, Hirna, Langey, and Qarsa) fell below the sufficiency range. No potato leaf samples from any of the farms had an excess level of the nutrient. The analysis of variance also revealed that the villages differed significantly ($P < 0.05$) in N concentration in potato leaves (Table 2).

Phosphorus

The leaf P concentration (Table 2) ranged between 1.1-5.0 mg g^{-1} dry matter (0.11–0.50%). The overall mean values fell within the sufficiency range reported for the crop. However, the mean concentrations of the nutrient in the leaf tissues sampled from five villages (Haramaya, Hirna, Kombolcha, Langey, and Watar) were below the sufficiency range. In this respect, the values obtained from only two villages, namely, Arbarakkate and Qarsa fell within the sufficiency range. Furthermore, no samples from any other farms had concentrations of the nutrient nearing the upper value of the sufficiency range established for the crop. As indicated in Table 2, the concentrations of P in leaves of potato plants sampled from the different villages varied significantly ($P < 0.05$).

Potassium

The concentration of K in the leaf ranged from 29.7–51.1 mg g^{-1} dry matter (2.97–5.11%). In general, potato leaves sampled from farms in each village had a mean K concentration that was within the sufficiency range but certainly nowhere near its upper range. It, however, emerged that the tissue K concentrations of plants originating from the different villages were significantly ($P < 0.05$) different (Table 2).

Sulphur

The leaf S concentration of potato plants sampled from the entire surveyed region varied from 3.6–6.7 mg g^{-1} dry matter (0.36–0.67%), and fell within the sufficiency range reported for the crop in the literature. Furthermore, leaf S concentrations of plants from all surveyed villages lay above the lower range of sufficiency. Like the leaf concentrations of other macronutrients, leaf S concentrations from the different villages varied significantly at $P < 0.01$ (Table 2).

Calcium

The leaf Ca concentration ranged between 10.4–24.4 mg g^{-1} dry matter (1.04–2.44%), which was, depending upon the villages, mostly within, with some above the sufficiency range reported for the crop. However, the overall mean value indicated its sufficiency level in the leaf tissues. Like the other macronutrients, the analysis of variance revealed significant ($P < 0.01$) variations in potato leaf Ca concentrations among the villages (Table 2).

Magnesium

The concentration of Mg in the leaf tissues (Table 2) varied from 3.8–11.1 mg g^{-1} dry matter (0.38–1.11%). Some of these values, however, were within and others were above the upper range of sufficiency reported for the crop in the literature. The overall mean was just above the sufficiency range. In conformity with the results obtained for Ca, the leaf Mg concentrations of potato plants sampled from the various villages also differed significantly.

3.2. Concentrations of Micronutrients in Leaves

Boron

The concentration of B in the leaf tissue varied from 26.8–57.6 mg kg^{-1} dry matter (Table 3). The upper value of this range was slightly above the sufficiency range for the crop; however, the overall mean was within the sufficiency range. The leaf concentrations of this micronutrient, like the concentrations of the macronutrients, differed significantly ($P < 0.05$) across the villages.

Copper

Foliar Cu concentration varied from 10.8–34.2 mg kg^{-1} dry matter (Table 3) with the mean value being above the sufficiency range. However, no toxic level of the nutrient was detected in any of the leaf samples. In this case too, the Cu concentration differed significantly ($P < 0.01$) across the villages.

Iron

The concentrations of Fe in the leaf tissues of potato plants sampled from all surveyed farms ranged from 21.8 – 123.9 mg kg^{-1} dry matter (Table 3). The results showed that some of the samples had Fe concentrations below the sufficiency range whereas most had concentrations of the nutrient falling within the sufficiency range. The overall mean also fell within the sufficiency range. Concentrations of the nutrient that fell below the sufficiency range came from the villages of Haramaya and Watar. No toxic level of the nutrient, however, was detected in the plant tissue. The leaf concentrations of the nutrient also differed significantly ($P < 0.01$) across the villages (Table 3).

Manganese

Manganese (Mn) concentration in the leaves of potato plant ranged from 5.4–75.5 mg kg^{-1} dry matter, with a mean that fell just within the sufficiency range (Table 3). However, the potato plants sampled from the village of Watar fell short of the sufficiency range of Mn required for optimum growth of the crop. In addition, leaf samples collected from all villages had Mn concentrations that were near the lower limit of the sufficiency range, and none of the leaf samples had Mn concentration that fell above the sufficiency range. No toxic concentration of the nutrient was detected in the leaf tissues. However, the concentrations of Mn in the leaf tissue of potato plants sampled from all sites were in statistical parity

Table 2. Concentrations (mg g^{-1} dry matter) of macronutrients (mean ± SD) in potato leaves sampled from 70 smallholder farms in seven villages in the eastern highlands of Ethiopia.

District	N	P	K	S	Ca	Mg
Arbarakkate	45.8±7.6^{a}	4.1±0.7^{a}	39.7±5.4^{ab}	5.1±0.3^{a}	18.6±2.1^{abc}	7.9±1.3^{a}
Haramaya	32.0±7.6^{b}	2.3±0.9^{c}	35.8±4.6^{b}	4.8±0.7^{ab}	20.4±5.8^{ab}	7.6±1.9^{ab}
Hirna	33.7±2.8^{b}	2.7±0.3^{bc}	38.6±2.6^{ab}	4.8±0.2^{ab}	18.6±2.1^{abc}	7.3±1.3^{ab}
Kombolcha	41.7±6.5^{a}	2.4±0.3^{bc}	41.7±6.1^{a}	4.6±0.5^{ab}	16.3±3.8^{bc}	7.7±1.8^{ab}
Langey	31.2±3.6^{b}	2.4±0.5^{bc}	40.4±2.8^{ab}	4.9±0.4^{ab}	17.3±1.5^{abc}	6.1±1.1a^{bc}
Qarsa	32.7±3.2^{b}	3.2±0.5^{b}	41.9±3.0^{a}	4.4±0.2^{b}	15.9±1.5^{c}	6.0±1.5^{bc}
Watar	43.1±6.3^{a}	2.4±0.4^{c}	37.9±1.8^{ab}	4.7±0.4^{ab}	21.3±2.5^{a}	5.3±0.8^{c}
CV (%)	13.7	19.8	10.8	9.3	17.2	19.8
F-test (Tukey)	*	**	*	**	**	**
Range	23.3 – 50.7	1.1 – 5.0	29.7 – 51.1	3.6 – 6.7	10.4 – 28.4	3.8 – 11.1
Mean	37.1	2.9	39.4	4.8	18.4	6.9
Median	35.3	2.8	39.3	4.7	17.9	6.6
Sufficiency range	35 – 45^{a}	2.5 – 6.0^{a}	35 – 50^{a}	2.0 – 5.0^{a}	6.0 – 20^{a,b}	3.0 – 6.^{0a,b}
Toxic^{a}	> 65	> 12.5	> 65	–	–	–

*Means followed by the same letter within a column are not significantly different at 5% level of significance according to Tukey Test; * = Significant at 0.05; ** = Significant at 0.01; NS = Non-significant; SD = Standard deviation; CV= Coefficient of Variation; for each village, the mean value represents 10 potato farms; the sample from each farm consisted of 60 leaves (leaf + petiole); [a]Walworth and Muniz (1993); [b]Bergmann (1993).*

Table 3. Concentrations (mg kg^{-1} dry matter) of micronutrients (mean ± SD) in potato leaves sampled from 70 smallholder farms in seven villages in the eastern highlands of Ethiopia.

District	B	Cu	Fe	Mn	Mo	Zn
Arbarakkate	42.9±5.3^{a}	24.1±4.3^{bc}	58.6±17.3^{ab}	39.7±18.8	6.6±2.5^{a}	47.3±6.2
Haramaya	37.7±6.1^{ab}	23.8±4.6^{bc}	33.8±17.2c	41.7±24.0	5.7±1.9^{ab}	42.8±18.6
Hirna	40.5±2.9^{ab}	26.9±4.7^{ab}	60.2±16.4^{ab}	38.2±10.7	6.0±2.0^{ab}	41.5±6.0
Kombolcha	39.8±7.9^{ab}	20.9±1.9^{c}	76.7±29.8^{a}	40.2±21.7	3.9±1.6^{b}	37.5±8.3
Langey	35.3±3.6^{b}	30.7±2.8^{a}	65.9±14.0^{a}	41.3±11.4	4.7±1.0^{ab}	44.7±6.5
Qarsa	35.9±3.2^{b}	25.5±1.6^{abc}	63.4±14.4^{a}	54.6±6.9	3.8±1.1^{b}	37.6±2.6
Watar	39.7±6.3^{ab}	29.3±3.0^{a}	36.2±21.1^{bc}	33.2±21.1	5.8±1.4^{ab}	47.2±3.5
CV (%)	12.6	14.6	31.7	39.8	31.7	21.2
F-test (Tukey)	*	**	**	NS	**	NS
Range	26.8 – 57.6	10.8 – 34.2	21.8 – 123.9	5.4 – 75.5	2.0 – 9.9	26.2 – 80.6
Mean	38.8	25.8	56.4	41.5	5.2	43.5
Median	38.5	25.9	55.4	44.9	4.9	42.7
Sufficiency range^{a,b}	25 – 50	5 – 20	40 – 200	40 – 200	0.2 – 0.5	25 – 60
Toxic^{a,b}	> 55	> 50	> 500	> 400	–	>150

*Means followed by the same letter within a column are not significantly different at 5% level of significance according to Tukey Test; * = Significant at 0.05; ** = Significant at 0.01; NS = Non-significant; SD = Standard deviation; CV = Coefficient of Variation; for each village, the mean value represents 10 potato farms; the sample from each farm consisted of 60 leaves (leaf + petiole); [a]Walworth and Muniz (1993); [b]Bergmann (1993).*

Molybdenum

Leaf Mo concentration ranged from 2.0–9.9 mg kg^{-1} dry matter (Table 3). The mean concentration of the nutrient exceeded the sufficiency range, amounting to 10-fold higher than the sufficiency range reported for the crop in the literature. Besides, leaf Mo concentrations varied significantly ($P < 0.01$) across the villages.

Zinc

Leaf Zn concentration varied from 26.2 – 80.6 mg kg^{-1} dry matter (Table 3). Leaf samples from some villages had Zn concentrations that fell within the sufficiency range whilst others had values exceeding the sufficiency range. However, the overall mean value was within the sufficiency range, but with some isolated samples from Haramaya village exhibiting concentrations that surpassed the upper range. However, no toxic level of the nutrient was detected in any of the leaf samples. Unlike the results obtained for most of the micronutrients, leaf zinc concentrations did not vary among samples collected from the different villages (Table 3).

3.3. Concentrations of Mineral Nutrients in Tubers

Concentrations of the major nutrients (N, P and K) and those of the secondary nutrients (Ca and Mg) in tubers and the ranges thereof for comparison are shown in Table 4.

Table 4. Concentrations (mg g dry matter^{-1}) of selected mineral nutrients in tuber tissue of potato plants harvested from 42 smallholder potato farms from seven villages in the eastern highlands of Ethiopia.

District	N	P	K	Ca	Mg
Arbarakkate	17.4^{a}	3.0^{a}	21.3^{ab}	1.5^{c}	6.4
Haramaya	11.5^{b}	1.9^{b}	19.1^{ab}	2.4^{ab}	6.4
Hirna	12.3^{b}	2.0^{b}	18.9^{b}	1.5^{c}	6.3
Kombolcha	13.8^{ab}	2.4^{ab}	20.5^{ab}	1.8^{bc}	6.6
Langey	9.8^{b}	1.8^{b}	22.0^{a}	2.0^{abc}	6.1
Qarsa	11.6^{b}	2.4^{ab}	19.7^{ab}	1.7^{bc}	5.9
Watar	10.2^{b}	1.8^{b}	21.2^{ab}	2.7^{a}	5.8
CV (%)	27.6	25	10.7	29.9	11.6
F-test (Tukey)	*	**	*	**	NS
Range	6.4 – 27.1	1.2 – 3.6	14.1 – 25.0	0.9 – 3.9	4.7 – 7.7
Mean	11.6	2.1	19.2	2.0	6.4
Median	10.9	2.0	19.3	1.9	6.5
SD	4.59	0.47	2.63	0.81	0.73
Sufficiency range[a,b]	13.8 – 17.6	2.0 – 2.4	17.0 – 20	0.4 – 1.2	1.0 – 1.3
Toxic range	-	-	-	-	-

*Means followed by the same letter within a column are not significantly different at 5% level of significance according to Tukey Test; * = Significant at 0.05; ** = Significant at 0.01; NS = Non-significant; SD = Standard deviation; dm = Dry matter; CV= Coefficient of Variation; for each village, the mean value represents six potato farms; thirty representative tubers taken for analyses were collected from 60 plants in each farm;* [a]*Walworth and Muniz (1993);* [b]*Bergmann (1993).*

Nitrogen

Tuber N concentration ranged from 6.4–27.1 mg g^{-1} dry matter (0.64–2.71%), with a mean of 11.6 mg g^{-1} dry matter, which fell short of the sufficiency range required for production of quality tubers (Table 4). The N concentrations of the tubers sampled from villages other than Arbarakkate and Kombolcha fell short of the sufficiency range. On the other hand, no village produced tubers which N concentrations exceeding the sufficiency range. The tuber N concentrations also varied significantly ($P < 0.05$) across the villages. A good correlation ($R^2 = 0.78$) was obtained between leaf and tuber N concentrations. Accordingly, 78% of the variations in tuber N concentrations were explicable by the leaf N concentrations (Figure 2).

Phosphorus

Tuber P concentration varied from 1.2–3.6 mg g^{-1} dry matter (0.12–0.36%), with a mean of 2.1 mg g^{-1} dry matter (Table 4). The overall mean concentration of this nutrient in tuber tissue fell just within the sufficiency range reported for the crop in the literature. However, the mean tuber concentrations of the nutrient from three out of the seven villages fell short of the sufficiency range required for producing good quality tubers. The tuber P concentration varied significantly ($P < 0.01$) across the villages (Table 4). The maximum concentration of the nutrient was recorded for tubers sampled from Arbarakkate village. In this case too, a good correlation ($R^2 = 0.73$) was obtained between leaf and tuber P concentrations, explaining 73% of the linear relationship (Figure 3).

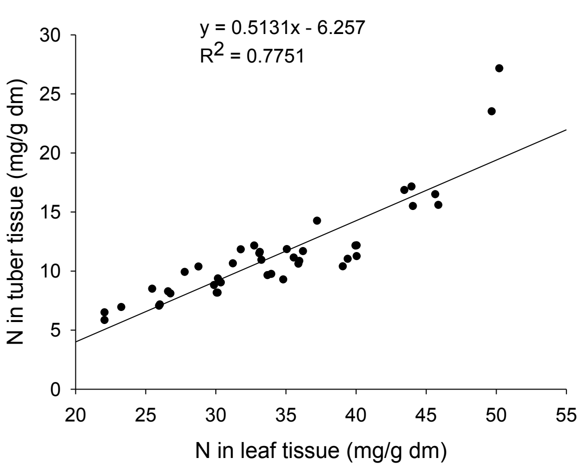

Figure 2. Relationship between leaf and tuber N concentrations.

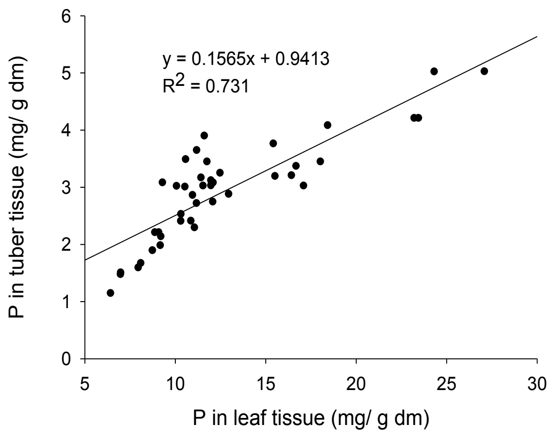

Figure 3. Relationship between leaf and tuber P concentrations.

Potassium

Tuber K concentration varied from 14.1–25.0 mg g^{-1} dry matter (1.41–2.50%), with a mean amounting to 19.2 mg g^{-1} dry matter, which was well within the sufficiency range reported for the crop (Table 4). No leaves sampled from any of the villages had concentrations of K that fell either below or above the sufficiency range. The villages differed significantly ($P < 0.05$) in tuber K concentration. There was a good correlation ($R^2 = 0.66$) between leaf and tuber K concentrations, explaining 66% of the linear relationship (Figure 4).

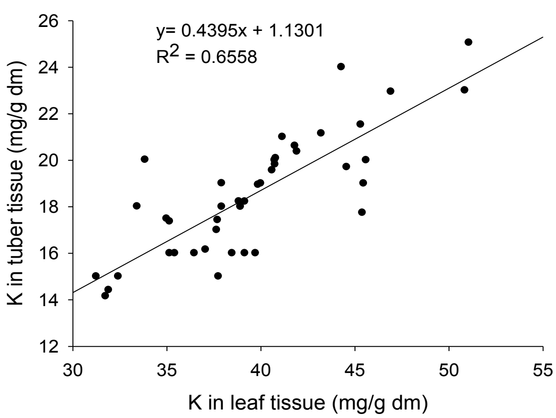

Figure 4. Relationship between leaf and tuber K concentrations.

Calcium

Tuber Ca concentration ranged between 0.9 and 3.9 mg g^{-1} dry matter (0.09–0.39%), with a mean of 2.0 mg g^{-1} dry matter. Compared to the sufficiency range (Table 4), the range, mean, and median values of tuber Ca concentrations from all farms in the seven villages were high. Moreover, the villages differed significantly ($P < 0.01$) with regard to the concentration of the nutrient in the tuber tissue. The maximum concentration of Ca was obtained from tubers sampled from the village of Watar, closely followed by those sampled from the villages of Haramaya and Langey (Table 4). There was also a good correlation ($R^2 = 0.77$) between leaf and tuber Ca concentrations. Thus, 66% of the concentration of the nutrient in the tuber tissue was explained by its concentration in the leaf tissue (Figure 5).

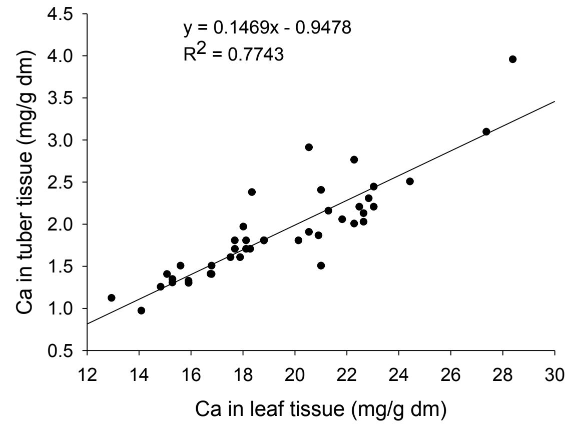

Figure 5. Relationship between leaf and tuber Ca concentrations.

Magnesium

The concentration of Mg in tubers varied from 4.7 to 7.7 mg g^{-1} dry matter (0.09–0.39%), with a mean of 6.4 mg g^{-1} dry matter. Clearly, this range is much higher than the sufficiency range commonly reported for the crop in the literature. However, the villages did not produce tubers with significant ($P > 0.05$) differences in Mg concentrations (Table 4). The correlation ($R^2 = 0.61$) between leaf and tuber Mg concentrations was nearly medium, explaining only 61% of the linear relationship (Figure 6).

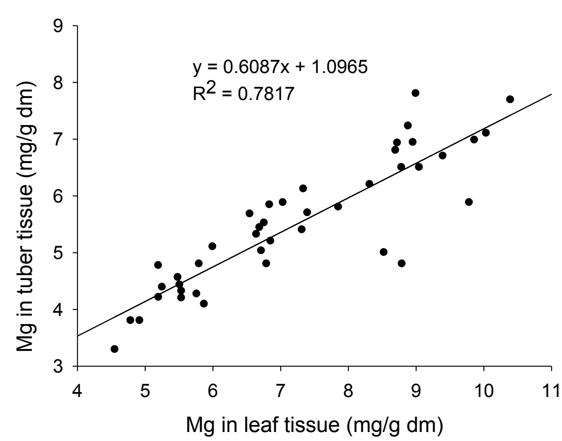

Figure 6. Relationship between leaf and tuber Mg concentrations.

4. Discussion

4.1. Mineral Nutrient Concentrations in Potato Leaves

The sufficiency ranges of potato leaf nitrogen (3.5–4.5%), phosphorus (2.5–6.0%), and potassium (3.5–5.0%) concentrations suggested by Walworth and Muniz (1993) were used for comparison in this study. These ranges are moderate and applicable to diagnosing leaf tissue N, P, and K concentrations of potato plants grown in Ethiopia, whose yields are low compared to the sufficiency ranges of nitrogen (5.0–6.5%), phosphorus (4.0-6.0%), and potassium (5.0–6.6%) reported by Bergmann (1993), which basically apply to high yielding potato crops in the temperate regions (Prummel and Barnau-Sijthoff, 1984). Similarly, tuber N, P, K, Ca and Mg concentration ranges reported by Walworth and Muniz (1993) were used as a reference in this study. However, for comparing leaf concentrations of secondary nutrients (Ca, Mg and S) as well as micronutrients (B, Cu, Fe, Mn, B, Mo and Zn), the comparable sufficiency ranges suggested by both authors were used.

Nitrogen, Phosphorus, and Potassium

In view of the ranges of nutrient concentrations in the leaf tissue of potato plants reported in the literature, most of the plants that originated from the seven potato growing villages were deficient in nitrogen and phosphorus. These results signify that availability or uptake of the two nutrients is a major factor limiting productivity of the potato crop in the region. This may partly explain the low average tuber yield of the crop obtained by smallholder farmers in the region, which ranges between 11-13 t ha^{-1} (Mulatu *et al*., 2005).

The deficient status of nitrogen and phosphorus in the potato plants surveyed from the region may be attributed to low application of fertilizers by smallholder farmers. Corroborating this suggestion, Gildemacher *et al*. (2009) reported that potato farmers in the central highlands of Ethiopia applied on average only 3.0 t manure, 30.6 kg N, and 33.4 kg P ha^{-1}, respectively. This indicates that farmers grow the crop under sub-optimal levels of soil nitrogen and phosphorus. The observed variations in the status of nitrogen and phosphorus in potato plants across the villages may be attributed to inherent variability in soil fertility status among the villages (Zewdie, 1999). The sufficient status of nitrogen and phosphorus in potato leaves and tubers originating from the villages of Arabarakkate and Kombolcha imply that the farmers in the two villages either applied considerable amounts of manure and/or mineral fertilizers, which is mostly induced by the availability of profitable informal cross-border market outlets in neighbouring Djibouti and Somalia (Mulatu *et al*., 2005; Hirpa *et al*., 2010). The high status of the two nutrients in potato plants originating from the two villages may also be ascribed to the fact that these areas were covered with natural forests a few decades ago (EMA, 1988) before being opened to cultivation, and had better soil organic matter and total nitrogen reserves (Mulugeta *et al*., 2005).

The survey results, however, revealed that the concentrations of potassium in the leaf tissue of the potato plants from all villages were sufficient. This suggestion is consistent with the report of Murphy (1959) that most Ethiopian soils, especially those in eastern Ethiopia, are rich in available potassium. However, the disparities observed in the leaf potassium concentration indicate inherent variability in the availability of the nutrient in soils across the villages. In addition, leaf K concentrations of plants from all of the villages were near the lower range of sufficiency and there was no concentration that approached the upper range of sufficiency. This may suggest that depletion of the nutrient from the soil is taking place in the face of intensified cropping and high uptake of the nutrient by crops. The problem is exacerbated by absence of return of crop residues back to the farmlands and no application of the nutrient from external sources. This suggestion is in accord with the results of Poss *et al*. (1997) who reported that K balance was strongly negative when straw was removed from a farm in Mali. This means that soil potassium reserves would run down and cannot sustain crop production in the long run. Therefore, increasing potato yield and quality in the study area may not be guaranteed in the future without integrated application of external sources of the major mineral nutrients.

Calcium, Magnesium and Sulphur

The sufficient leaf Ca, Mg and S concentrations of potato plants sampled from all seven villages are consistent with the sufficiency ranges reported by Bergmann (1993) and Walworth and Muniz (1993). The results imply that potato yield and tuber quality are unlikely to be constrained by deficiencies of these nutrients in the study areas. The ample concentrations of the three nutrients in the potato leaves may be attributed to their high availability in the soils. This may be ascribed to the nature of the soil parent material, which is mainly granite that contains carbonates and sulphates of calcium, magnesium, and calcium (Hawando, 1984). This suggestion is consistent with the reports of Uloro (1999) and Zewdie (1999) that most of the parent materials of the soils occurring in the eastern highlands of the country include volcanic rocks such as granites, gneiss and syenites and sedimentary rocks such as lime stones, shale and sandstones, which have ample contents of calcium, magnesium, and sulphur.

Boron, Copper, Iron, Manganese, Molybdenum, Zinc

The adequate concentrations of most of the micronutrients in potato leaf tissues sampled from most of the surveyed farms are consistent with the micronutrient sufficiency ranges reported for the crop by Bergmann (1993) and Walworth and Muniz (1993).

However, iron deficiency in leaf samples originating from Haramaya and Watar villages as well as manganese deficiency in leaf samples from Hirna, and Watar villages should be a matter of concern for potato production in the area. The low concentrations of iron and manganese in leaves sampled from these villages could be attributed to the richly calcareous nature of the soils, which reduces their uptake by roots, causing calcium-induced chlorosis (Lindsay and Schwab, 1982; Vose, 1982; Mori, 1999). This result is concordant also with that of Lindsay (1979) who reported that manganese deficiency mostly occurred in calcareous soils having pH ranging from 7.3–8.5. On the other hand, the leaf Mo concentration that was 10-fold higher than the sufficiency range established for the crop indicates ample uptake of the nutrient possibly due to favourable soil conditions such as high pH (> 5.5) (Hazelton and Murphy, 2007). Interestingly, on the other hand, absence of molybdenum toxicity in the potato leaves could be attributed to the wide intervals between its critical deficiency and toxicity levels (Marschner, 1995). This suggestion is consistent with the findings of Gupta (1997) that it was leaf tissue concentration of molybdenum as high as or higher than 500 mg Mo kg^{-1} dry matter that would lead to a toxic response in plants. The sufficient status of boron, copper, and zinc in leaves originating from all villages may be associated with the parent material of the soil, which may inherently contain sufficient amounts of the nutrients.

4.2. Mineral Nutrient Concentrations in Potato Tubers

Maier (1994) showed that tuber N, P and K concentrations influence potato yield and tuber quality attributes such as specific gravity, crisp colour, and reducing sugar concentrations, which determine nutritional as well as processing values. Calcium and magnesium also have vital roles in determining tuber quality attributes (Olsen *et al*., 1996; Karlsson *et al*., 2006).

Nitrogen, Phosphorus and Potassium

The P concentration in tubers obtained in this study is similar to the values obtained by Tekalign and Hammes (2005). The low N and P concentrations recorded for tubers sampled from most of the surveyed villages indicate that the yield and quality of potatoes produced there are constrained prominently by deficiencies of the two nutrients. However, the sufficiently high concentrations of N and P in tubers as well as leaves of the potato plants obtained from the villages of Arbrakkate and Kombolcha indicate the potential of these villages for production of tubers of higher yield and better quality, possibly due to better soil fertility management by the farmers or better soil fertility status in the areas.

The range of tuber K concentration obtained in this study is in agreement with published values (Tekalign and Hammes, 2005). Bergmann (1993) suggested that the concentration of K in tubers should range between 18 to 22 mg g^{-1} dry matter (1.8–2.2%) for high starch yield (processing) and between 22–25 mg g^{-1} dry matter (2.2–2.5%) for high tuber yield. The optimal K concentration in the dry matter of potato tubers for high yield ranged from 2.2–2.5% (Prummel, 1981; Winkelmann, 1992). In fact, tubers with greater than 2.2% K concentration are not apparently suitable for processing as excess K lowers tuber dry matter yield (Westermann, 1994). This would make potato tubers unfit for processing due to the concomitant low specific gravity (dry matter), but increases the volume of fresh tuber yields (Prummel, 1981; Bergmann, 1993). Potato tubers with low specific gravity yield fewer products per unit of raw material and the product obtained is less rigid, crisp and more oily (Storey and Davies, 1992). According to Gould (1999), the cut-off below which factory deliveries are not acceptable is 19.5% of dry matter (SG = 1.077) for French fries and 20% of dry matter (SG = 1.079) for chips.

Compared to the slightly higher optimal tuber K concentration threshold values reported by other researchers (Prummel, 1981; Winkelmann, 1992; Bergmann, 1993), Walworth and Muniz (1993) reported an optimal range of 17–20 mg kg^{-1} dry matter (1.7-2.0%) for both high yield and quality of the crop at maturity, which was 90 to 95 days after planting. Therefore, a limitation in tuber K status is unlikely to be a cause of low potato yield and quality in all surveyed villages in the region. In fact, the sufficient status of K in tubers sampled from all villages mirrored the sufficient status of the nutrient in the leaves.

Calcium and Magnesium

Calcium and Mg concentrations in tuber samples obtained from all villages were above the sufficiency range reported for the crop in the literature. The values were 10-fold higher than the results reported by Tekalign and Hammes (2005). The very high Ca and Mg concentrations are inexplicable, but could imply very high availability of the two nutrients in the soil for plant uptake (Murphy, 1968). The very high Ca concentration may also be attributable to the phenomenon of absorption of the nutrient directly from the soil solution through tuber periderm (Davies and Millard, 1985). A problem that may occur with elevated Ca and Mg levels is reduced uptake of other cations due to competition for uptake sites at the roots (Marschner, 1995). On the other hand, a high calcium concentration in tubers has benefits. It increases tuber quality and storability (Olsen *et al*., 1996) since the nutrient is responsible for increasing tuber firmness (Karlsson *et al*., 2006). Therefore, potato tubers produced by smallholder farmers in the study area are likely to have a good storage quality or shelf life.

Tuber N, P, K, Ca, and Mg concentrations were found to be a reflection of the amounts of concentrations of the nutrients in the leaves as demonstrated by the correlation analysis. This indicates that mineral nutrients in leaves are eventually translocated to tubers (White *et al*., 2009), implying that sufficient supply and uptake of nutrients by the potato plant is essential for both high yield and quality of the crop.

5. Conclusions

The results of this study demonstrated that N and P were deficient in potato leaves sampled from nearly 60% of the surveyed villages. However, concentrations of all other macronutrients were sufficient in leaves sampled from all villages. Tubers sampled from about 70% of the villages were deficient in N whereas those sampled from about 43% were deficient in P. Tubers from all villages were sufficient in K, Ca, and Mg concentrations. On the other hand, concentrations of all micronutrients were sufficient in leaves sampled from all villages except Fe and Mg, which were deficient in leaves sampled from a couple of villages. The correlation analysis showed that the magnitude of tuber N, P, K, Ca, and Mg concentrations was dependent upon the magnitude of the concentrations of the minerals in leaves. This suggests that adequate uptake of mineral nutrients by roots and their increased concentration in leaves is necessary for adequate concentrations of the nutrients in tubers. In fact, compared to the other five villages, better nourished potato plants in terms of both leaf and tuber nutrient concentrations were obtained from the villages of Arbrakkate and Kombolcha. This indicates superior potential of these areas for potato production. It could be concluded that severe deficiencies of N and P in both leaves and tubers were major factors constraining potato production in the study areas. Isolated Fe and Mn deficiencies should also be a matter of concern. Therefore, efficient and integrated fertilizer programmes should be formulated with a particular emphasis on enhancing the composition of N and P in potato leaves and tubers to improve both the yield and quality of the crop in the region.

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