Yield of potato (*Solanum tuberosum* L.) increased by more than two-folds through nitrogen and phosphorus fertilizers in the highlands of North-Western Ethiopia

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ABSTRACT

Ethiopia has a huge potential to increase the production and productivity of potato (*Solanum tuberosum* L.) mainly in north-western regions where current potato yields are less than 10 t ha⁻¹. Soil fertility and disease are the major yield-limiting factors of potato in this part of the country. Three-year’s on-farm research was conducted to get the optimum economic levels of nitrogen (N) and phosphorus (P) nutrients for the major potato-growing areas of north-western Ethiopia. A factorial experiment with four levels of N (46, 92, 138, and 194 kg ha⁻¹), three levels of P2O5 (46, 69, and 92 kg ha⁻¹), and one pilot treatment with no NP nutrient inputs was used. A randomised complete block design with three replications was used. The findings of the research showed that more than 40 t ha⁻¹ of potato could be attained (about four times the current productivity) in the study areas through NP nutrient management. The yield was increased significantly with an increased rate of N at all sites (*p < 0.01*). The yield difference was non-significant (*p > 0.05*) between P levels for most of the sites and years. The financial analysis of the findings for Yilmana Densa district indicated that applying 138 N and 46 P2O5 kg ha⁻¹, together, gave a marginal return of (Birr/Birr) 70.9, whereas 138 N and 69 P2O5 kg ha⁻¹ resulted in 10.7. For the South Gondar, 138 N and 46 P2O5 kg ha⁻¹ gave a marginal return of 24.3 (Birr/Birr). Therefore, based on the farm gate price of potato and the cost of fertilizer, 138 N, combined with 69 P2O5 kg ha⁻¹, is recommended for the Yilmana Densa. For the South Gondar, 138 N, combined with 46 P2O5 kg ha⁻¹, is recommended.

1. Introduction

Potato (*Solanum tuberosum* L.) is one of the dominant crops globally, ranking fourth in terms of volume of production and area coverage (FAOSTAT, 2007; Tkachenko et al., 2021). In Ethiopia it ranks first among root and tuber crops (CSA, 2016). Potato is characterised as a cheap and nutritious food security crop. Because of its high yield with good nutritious values per unit area and per unit of time compared with other major cereal crops (Kanter and Elkin, 2019; Beals, 2019), it is considered as a food and nutrition security crop. Potato was one of the strategic crops identified in the United Nation’s Millennium Development Goals for achieving food security and poverty eradication and as a result the year 2008 was designated as the year of potato by the United Nations. Its contribution to food security with a stable price might be continued, as the price of potato mainly depends on local demand and supply than on the global market. Potato’s short cycle and early-maturing habits are additional benefits to intensification over many other crops.

Ethiopia has an immense potential to boost the productivity of potato (*Solanum tuberosum* L), especially in the highlands (Woldegiorgis et al., 2013; Haverkot et al., 2012). About 70% of the cultivated land of Ethiopia is suitable for potato production (FAO, 2008) but only 2% of the potential has been exploited (Hirpa et al., 2015). About 40% of potato producers are concentrated in the north-western parts of Ethiopia: south Gondar, north Gondar, east Goji, west Gojiam, and Aew Awi administrative zones, the Amhara National Regional State of Ethiopia (Hirpa et al., 2015), that could be related to agro-ecological suitability.
However, these areas are characterised by a high population density with less food and nutrition security. Thus promoting high-yielding crops including potato is highly recommended under such situations (De Jong, 2016). The Ethiopian Agricultural Research System placed its national potato research coordination at Adet Agricultural Research Centre (West Gojjam) based on the existing potential of potato in this parts of the country. The current state of potato productivity in Ethiopia is less than 10 t ha\(^{-1}\) (Dersseh et al., 2016; Hassen et al., 2015; Haverkort et al., 2012; Hirpa et al., 2015), Figure 1, and its total annual production is only about 0.5 million tonnes (Table 1).

On the other hand, Haverkot et al. (2012) reported the highest record yield of potato (64 t ha\(^{-1}\)) around Shashemene in the rift valley of Ethiopia, indicating high variability of productivity in the country governed by different biotic and abiotic factors. Ethiopian soils have been depleted because of negative input-to-output balances of the nutrients (low soil fertility) that could contribute to the high variability and low crop productivity, including potato (Amare et al., 2013a, b, 2018; Amare et al., 2013a, b; Hirpa et al., 2012; Kebede and Ketema, 2017; Muleta and Aga, 2019). Among plant nutrients, nitrogen (N) and phosphorus (P) are so far the most yield-limiting nutrients of cereal crops in Ethiopia (Amare et al., 2018, 2022a), whereas for potato N is the most yield-limiting nutrient (Muleta and Aga, 2019). However, the need to identify and update the biological and financial response of potato to N and P is a critical gap in north-western Ethiopia. Therefore, this research was conducted to obtain the biological and financial optimum rates of N and P for potato production to northwest Ethiopia.

2. Materials and methods

2.1. Study sites

Yilmana Densa is located about 42 km from Bahir Dar on the way to Addis Ababa through Mota and represents the potato-growing areas of west Gojjam, Agew Awi, and east Gojjam zones. The district is characterised by highland and midlands. It has a uni-modal rainfall with a mean of 1240 mm yr\(^{-1}\) (long term average), with June–August receiving the largest amount of annual rainfall. Its temperatures range from 9.3 °C to 25.7 °C. However, the annual rainfall during the research was 1058, 1208.7 and 1431.8 mm for year 1 (2016), year 2 (2017) and year 3 (2018), respectively. The distribution of the rainfall for both study sites during the experimental period is presented in Figure 2. The average minimum temperature for all the study years was 11 °C while the maximum mean temperatures were 26.7, 25.6 and 25.9 °C for year 1, year 2 and year 3 respectively. The local geology is volcanic basalt and Cenozoic pyroclastic fall deposits (Zewde, 2009) and the major soil properties are indicated in Table 2. Potato and food barley are the most important crops in the highlands of the district. The district is one of the most highly populated districts of the region which has led to very small farmland per capita. Farta and Laigaint are parts of the south Gondar Administration zone of the

![Figure 1. Potato productivity in Ethiopia.](research.cip.cgiar.org/confluence/display/wpa/Ethiopia) (accessed 8 January 2019).
Amhara National Regional State with rainfall patterns similar to those of Yilmana Densa (Figure 2). The total rainfall of south Gondar was 1360.7, 1300.9, and 1609.5 mm for year 1, year 2 and year 3, respectively. The mean minimum temperature for the study years was 9.8 for year 1 and year 2 while 9.5 for year 3. The mean maximum temperature remains similar (22.5) for year 1, year 2 and year 3. Potato and food barley are the dominant cultivated crops in these districts as well. The farming system of the study sites is subsistence and crop-livestock mixed type.

2.2. Treatment setup

The experiment was conducted for three years in the rainy season with three sites per location per year (three for Yilmana Densa and three for south Gondar (Farta and Laigaint). A factorial experiment with four levels of N (46, 92, 138, and 194 kg N ha$^{-1}$), combined with three levels of P (46, 69, and 92 P$_2$O$_5$ kg ha$^{-1}$) was used for the study. One treatment with no nutrient input (control) was also included to assess the current state of potato production without fertilizer application as there are potato growers who do not use fertilizer. Treatments were replicated three times and arranged in a randomised complete block design. Nitrogen was applied at three stages: one third at planting, one third three weeks after germination, and the final one third at flowering while the entire dose of P was applied at planting. Urea (46% N) and Triple Super Phosphate (46% P$_2$O$_5$) were sources of fertilizers for N and P, respectively. ‘Gudene’ is an improved potato variety developed by the Ethiopian Agricultural Research System and it is a well-known recommended variety in the study areas and hence used for the study. The distance between plants and rows was 0.3 and 0.75 m, respectively. The gross size of each plot was 13.5 m$^2$ (3 x 4.5 m). The data were collected from the central four rows with a plot size of 9 m$^2$ (3 x 3 m). Earthing up was uniformly applied at three weeks after germination. Redomil at the rate of 3 kg ha$^{-1}$ was applied uniformly for the control of late blight disease as soon as the disease appeared.

2.3. Soil sampling and analysis

Five soil samples per site were collected using soil auger at a depth of 0–20 cm and then one composite soil sample was prepared to assess the state of soil fertility for the experimental sites before planting. The samples were then air-dried, ground by mortar and pestle and sieved through 2 mm. Soil pH was determined in a 1:2.5 soil-to-water suspension following the procedure outlined by Sertsu and Bekele (2000). TN was determined following the procedure described by Sertsu and Bekele (2000). Soil organic carbon (SOC) content was determined by the wet digestion method using the Walkley and Black procedure (Nelson and Sommers, 1982). The available P was determined following the Olsen procedure (Olsen and Sommers, 1982). The exchangeable potassium (K) was measured by flame photometer after extraction of the samples with 1 N ammonium acetate at pH-7 following the procedures described by Sertsu and Bekele (2000).

2.4. Yield and yield related data

The data were collected from the central four rows with a plot size of 9 m$^2$ (3 x 3 m). The yield of tuber was collected at maturity. The farm gate price of potato was collected for each site. The cost of fertilizer was also collected from the respective sites (Yilmana Densa and South Gondar) as indicated below.

2.5. Data analysis

The effect of independent variables (N, P, and their interaction) on the dependent variable (potato tuber yield) was statistically tested. The analysis was made for each site and year and combined as well. Analysis...
of variance (ANOVA) was carried out to assess the difference between treatments. Upon the existence of significant difference for ANOVA \((p < 0.05)\), further analysis of mean separation was carried out using Least Significant Difference (LSD) at 5%. Graphical analyses were also employed to evaluate response curves over different doses of N and P nutrients. The partial budget analyses were done based on CIMMYT (1988). The cost of NPS and urea was, respectively, 1284.05 and 1158.58 Birr 100 kg\(^{-1}\). The farm gate price of potato (Birr 100 kg\(^{-1}\)) was 487 at Yilmana Densa and 450 Birr at south Gondar. Based on a 19 November 2021 exchange rate, one Birr Ethiopian Currency was equivalent to 0.0211 US dollar.

3. Results and discussion

3.1. Soils of the study sites

The pH of the soil for all the study areas was below 5.5 (Table 2), and hence it is considered as moderately acidic (FAO, 1984). Soil acidity is not a critical yield-limiting factor of potato for the study sites. Potato is tolerant of acid soils. The SOC content for Yilmana Densa was below 1.8% and for South Gondar it was about 1–2%. Accordingly, the soils of Yilmana Densa were below the critical levels of SOC, whereas those of south Gondar ranged from below to critical levels (Loveland and Webb, 2003; Murphy, 2014). It was similar with other findings for the cultivated lands of Ethiopia (Amare et al., 2022a, 2022b; Amare, 2018; Amare et al., 2013a, b). Generally, soils of the study areas were low in SOC that limits the supply of nutrients including N and P (Murphy, 2014). Therefore, for optimum production of potato, nutrients must be supplied in the forms of synthetic fertilizer, organic fertilizer, or in combination. The exchangeable K was about 0.7–0.9 cmol\(_{c}\) kg\(^{-1}\) of soil for Yilmana Densa, whereas for South Gondar it was 0.5–0.60 cmol\(_{c}\) kg\(^{-1}\) of soil. The result of soil analysis on soil K was above the critical levels for all the study sites (IPF, 2016). This indicated that at present, K is not yield limiting for the production of annual crops, including potato, for the study areas as supported by the findings of Amare et al. (2018). The mean values of the total nitrogen were: 0.18 and 0.14% for Yilmana Densa and South Gondar respectively. The available P of Yilmana Densa was below 11 ppm, which was below the critical levels (Huygens and Saveyn, 2018). For South Gondar it was highly variable (from 10 to 20 ppm).

3.2. Yield response to applied nitrogen and phosphorus

There was a high response of potato to applied NP (Figure 3). The response was higher to N than P (Figure 3, Tables 3 and 4). There was no

![Figure 3. Response of potato at Yilmana Densa and South Gondar to N (A) and P (B).](image)
any yield penalty for higher N application, rather there was an increase in yield even at the rates of 194 kg N ha\(^{-1}\) for all sites and for all seasons (Figure 3A). However, the yield response to the applied P was not as strong as the response to N (Figure 3B). The higher yield gap for the application of P was only observed between the control (no fertilizer) and treatments with P (Figure 3B). A long flat segment between the rates of phosphorus (46 kg P\(_2\)O\(_5\) ha\(^{-1}\) and above this treatment) as shown in Figure 3 indicates weak yield response to the applied phosphorus for all sites over all seasons.

The ANOVA results of the research showed a significant yield difference (\(p < 0.05\)) for all sites and years to N (Tables 3 and 4). Considering the main effects of N, the maximum tuber yield (40 t ha\(^{-1}\)) of potato was obtained in Yilmana Densa at a site called Chinkultit in the 2018 using 194 kg of N ha\(^{-1}\). This was four times the yield of potato from the control (without fertilizer). The average yield difference between P rates (Tables 3 and 4) except from control treatments (without fertilizer). The lowest rate of P (46 kg P\(_2\)O\(_5\) ha\(^{-1}\)) resulted in comparable tuber yield as that of the maximum rates (69 and 92 kg P\(_2\)O\(_5\) ha\(^{-1}\)) specifically to South Gondar.

Our finding on nitrogen was in line with the results of Getie et al. (2015) who recommended 110 kg N ha\(^{-1}\) for the major potato producing areas of Ethiopia although the rate they recommend was much lower than our finding. Nevertheless, Chindi (2019) reported phosphorus recommendation for potato production in the central Shoa of Ethiopia (90 kg P\(_2\)O\(_5\) ha\(^{-1}\)) that was at odds with our findings. The findings of Nyiraneza et al. (2017) in Canada also showed no response to P application under different soils with different levels of soil P that supports our finding: They recommended 150 kg N ha\(^{-1}\). Similarly, Setu and Mitiku (2020) reported that potato did not respond to P in western Ethiopia. Alemayehu and Jember (2018), under the Koga irrigation scheme, recommended 102 kg P\(_2\)O\(_5\) ha\(^{-1}\) for variety ‘Belete’ under low P conditions and 69 kg P\(_2\)O\(_5\) ha\(^{-1}\) for variety ‘Gudene’. For areas with sufficient P, they recommended 69 kg P\(_2\)O\(_5\) ha\(^{-1}\) for ‘Belete’ and 52 P\(_2\)O\(_5\) ha\(^{-1}\) for ‘Gudene’. Furthermore, Alemayehu and Jember (ibid.) claimed more than 30 ppm of available P (Olsen-P) at Koga irrigation scheme. On the other hand, the recommendations by Hassen et al. (2015) were somewhat in line with our findings for P (69 kg P\(_2\)O\(_5\) ha\(^{-1}\)), although their recommendation for N (80.80 kg N ha\(^{-1}\)) was much lower than our finding for north-western Amhara Region (Yilmana Densa and South Gondar). The recommendation of N made by Ayechew et al. (2009) in Vertisols of the Debere Birhan area (138 kg N ha\(^{-1}\)) was in line with our findings to all study sites. However, their recommendation for P was 20 kg P\(_2\)O\(_5\) ha\(^{-1}\) which is half what we found. Fixen and Bruulsema (2014), Pollain et al. (2009) and Kittipadalkul et al. (2016) suggested higher requirements of P to potato compared with other crops which is not observed in our finding where maximum yield was attained at lower P rates. Application of high rates of P without any significant biological yield increase could not only be economically unjustifiable, it also has an environmental risk (Ruark et al., 2014). Khakbazan et al. (2019) also used the rates of N and P (138–151 N and 69–75 kg P\(_2\)O\(_5\) ha\(^{-1}\)) which are similar to our findings and recommendations. In general, the yield of potato at Yilmana Densa could be improved by more than threefold (greater than 300%) and at South Gondar by more than two and a half-fold (greater than 250%) through nutrient applications (N) that is in line with the findings of Amare et al. (2022a, b), they reported that omitting nitrogen resulted in a non-significant yield of maize with no nutrient applications, regardless the high rates of phosphorus and potassium.

### 3.3. Partial budget analysis

The partial budget analysis was employed to identify the economical optimum rates of NP fertilizer for the production of potato. Farm gate prices for potato were 4.87 and 4.50 Birr kg\(^{-1}\) for Yilmana Densa and South Gondar respectively. The cost of fertilizer was 1284.05 and 1158.58 Birr for NPS and urea, respectively. The significant difference in the biological yield was reflected in the economic responses of the partial budget analysis as well. Some of the treatments with N/P\(_2\)O\(_5\) ha\(^{-1}\) (46/69, 46/92, 92/69, and 194/46 at Yilmana Densa and 46/69, 46/92, 92/92, 138/69, 138/92, and 194/46 at South Gondar) were dominated by the lower fertilizer rates (gave lower net benefits) and hence discarded from the analysis of marginal rate of return.

Accordingly, the highest marginal rate of return (70.9 Birr/Birr) for Yilmana Densa was found at the rates of 138 kg N ha\(^{-1}\) combined with 46 kg P\(_2\)O\(_5\) ha\(^{-1}\) (Table 5A). For South Gondar the maximum marginal rate of return (24.3 Birr/Birr) was found with 138 kg N ha\(^{-1}\) combined with 46 kg P\(_2\)O\(_5\) ha\(^{-1}\) (Table 5B). With the yield data of this research, the economic optimum rate could be continuously updated and adjusted to account for changes in market prices.
with respect to the farm gate price of potato and the cost of fertilizers. On the basis of the findings of this research, for Yilmana Densa and similar areas, 138 kg N ha\(^{-1}\) combined with 46 kg P\(_2\)O\(_5\) ha\(^{-1}\) is recommended as the first option and 138 kg N ha\(^{-1}\) combined with 69 kg P\(_2\)O\(_5\) ha\(^{-1}\) as the second option. For south Gondar 138 kg N ha\(^{-1}\) combined with 46 kg P\(_2\)O\(_5\) ha\(^{-1}\) are the profitable rates. The economic situation of farmers limits the use of the optimal amounts of fertilizer recommended by research (Gebru et al., 2017; Muleta and Aga, 2019). Alemayehu et al. (2020) found a very good marginal rate of return using 13.5 t ha\(^{-1}\) of farmyard manure combined with 245.1 kg NPS ha\(^{-1}\). Their finding is not in line with our finding, as they recommend high rates of P than N. Moreover, it is hard to apply 13.5 t ha\(^{-1}\).

4. Conclusion and recommendation

To improve the productivity of potato with economical feasible rates of fertilizers nitrogen and phosphorus, an intensive on-farm research was conducted for three consecutive rainy seasons in the north-western Ethiopia. The result showed that soil fertility management through fertilizer nitrogen and phosphorus significantly improved the productivity of potato. Tuber yield was increased by two and half-fold in the south Gondar while it was increased by three-fold in Yilmana Densa using NP fertilizers compared to the yield without fertilizer. Fertilizer nitrogen contributed the larger share to increase potato productivity; the response to N was stronger than the response to P. There was no yield penalty over the years by applying the maximum N rate (194 kg N ha\(^{-1}\)), rather the yield was increased with increasing N rates. Achieving yield to 40 t ha\(^{-1}\) in areas where less than 10 t ha\(^{-1}\) is produced has tremendous positive implications towards improving the food and nutritional securities for the potato growing belts (northwest Ethiopia), where 40% potato growers in the country exist. According to the finding of the research focus and priority to N fertilizer is critically important to maximally increase the productivity and profitability of potato production in the north-west Ethiopian highlands. To satisfy the existing high and increasing demand for potato throughout the country, application of optimum rates of fertilizer based on this research finding could lead to more production and profitable potato business. Therefore, for Yilmana Densa, 138 kg N ha\(^{-1}\) combined with 46 kg P\(_2\)O\(_5\) ha\(^{-1}\) are recommended as the first option, followed by 138 kg N ha\(^{-1}\) combined with 69 kg P\(_2\)O\(_5\) ha\(^{-1}\) as the second option. For south Gondar, 138 kg N ha\(^{-1}\) combined with 46 kg P\(_2\)O\(_5\) ha\(^{-1}\) is recommended. The economic recommendations may be subjected to changes based on the cost of fertilizers and price of the output (potato) changes. The yield of potato at south Gondar was lower than Yilmana Densa, indicating further research work is needed to improve the productivity in south Gondar.

Table 5A. Partial budget analysis for Yilmana Densa.

| Fertilizer rate | Fertilizer amount | Cost of Fertilizers | TC (in Birr) | Yield (t ha\(^{-1}\)) | TR (in Birr) | MC (in Birr) | MR (in Birr) | MRR (MR/MC) |
|-----------------|-------------------|---------------------|-------------|-----------------------|-------------|-------------|-------------|-------------|
| NPS Urea | 0/0 | 0 | 0 | 0 | 0 | 8.83 | 43002.1 | - | - |
| 46/69 | 121 | 50 | 1553.7 | 579.3 | 2133.0 | 16.84 | 82010.8 | 2133.0 | 36875.7 | 17.3 |
| 92/69 | 121 | 150 | 1553.7 | 1773.9 | 2317.2 | 23.15 | 112740.5 | 974.4 | 2970.3 | 3.0 |
| 46/46 | 121 | 50 | 1553.7 | 2896.5 | 4450.2 | 25.87 | 125986.9 | 184.2 | 13062.2 | 70.9 |
| 138/69 | 181.6 | 225 | 2331.8 | 2666.8 | 4938.6 | 27.04 | 131684.8 | 924.1 | 7793.2 | 10.7 |
| 194/69 | 181.6 | 346.7 | 2331.8 | 4016.8 | 6348.6 | 29.66 | 144444.2 | 924.1 | 7793.2 | 8.4 |
| 194/92 | 181.6 | 346.7 | 2331.8 | 4016.8 | 6348.6 | 29.66 | 144444.2 | 924.1 | 7793.2 | 8.3 |
| Where: TC = Total cost, TR = Total Revenue, MC = Marginal cost, MR = Marginal revenue, and MRR = Marginal Rate of Return.

Table 5B. Partial budget analysis for south Gondar.

| Fertilizer rate | Fertilizer amount | Cost of Fertilizers | TC (in Birr) | Yield (t ha\(^{-1}\)) | TR (in Birr) | MC (in Birr) | MR (in Birr) | MRR (MR/MC) |
|-----------------|-------------------|---------------------|-------------|-----------------------|-------------|-------------|-------------|-------------|
| NPS Urea | 0/0 | 0 | 0 | 0 | 0 | 7.54 | 33930.0 | - | - |
| 46/46 | 121 | 50 | 1553.7 | 579.3 | 2133.0 | 13.28 | 5850.0 | 2.6 | 12.1 |
| 92/69 | 121 | 150 | 1553.7 | 1773.9 | 2317.2 | 25.87 | 125986.9 | 184.2 | 13062.2 | 70.9 |
| 46/46 | 121 | 50 | 1553.7 | 2896.5 | 4450.2 | 25.87 | 125986.9 | 184.2 | 13062.2 | 70.9 |
| 138/69 | 181.6 | 225 | 2331.8 | 4016.8 | 6348.6 | 29.66 | 144444.2 | 924.1 | 7793.2 | 10.7 |
| 194/69 | 181.6 | 346.7 | 2331.8 | 4016.8 | 6348.6 | 29.66 | 144444.2 | 924.1 | 7793.2 | 8.4 |
| 194/92 | 181.6 | 346.7 | 2331.8 | 4016.8 | 6348.6 | 29.66 | 144444.2 | 924.1 | 7793.2 | 8.3 |
| Where: TC = Total cost, TR = Total Revenue, MC = Marginal cost, MR = Marginal revenue and MRR = Marginal Rate of Return.

Author contribution statement

Tadele Amare: Conceived and designed the experiment; Performed the experiment; Analyzed and interpreted the data; Wrote the paper.
Zerfu Bazie, Erkihu Alemu, Beamlaku Alemayehu, Abere Tenagne, Bitewlgn Kerebh, Yasin Taye, Abrham Awoke: Performed the experiment; Analyzed and interpreted the data; Wrote the paper.
Tesfaye Feyisa, Selamyihun Kidanu: Performed the experiment; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interest’s statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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