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Nutrient Use Efficiency Indices in Maize Hybrid as A Function of Various Rates of NPK in Mid Hills of Nepal

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ABSTRACT

Field experiments were conducted to evaluate yield and nutrient use efficiency in maize in response to various rates of nitrogen (N), phosphorus (P) and potassium (K) in silty clay loam soil of Khumaltar, Nepal during 2019 and 2020. Three factorial randomized complete block designs with 27 treatment combinations were used in experiments, which were repeated three times. Three factors were N levels (150, 180, 210 N kg ha^{-1}), P levels (40, 60, 80 P_2O_5 kg ha^{-1}), and K levels (40, 60, 80 K_2O kg ha^{-1}). The results recommend to revise fertilizer dose since N210 kg ha^{-1} and K_2O 80 kg/ha were optimum for increased maize production with grain yields of 10.95 t ha^{-1} and 10.54 t ha^{-1}, respectively. Partial factor productivity, partial nutrient budget, internal efficiency, physiological efficiency, recovery efficiency, and agronomic efficiency of NPK for hybrid maize were mostly influenced by nutrient levels. Application of higher rate of P and K fertilizer improved maize N efficiencies, and case was valid for P and K efficiencies. Maize was more responsive to N and K fertilizer and lower rate of P application limited efficient use of applied N and K. To increase overall NUE, we recommend to revise dose of fertilizer for hybrid maize under mid hill condition of Nepal.

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Introduction

Hybrid maize is a nutrient-responsive heavy feeder (Tetarwal et al., 2011) and has a high soil fertility requirement to achieve maximum yield (Uribelarrea et al., 2009). Hybrid maize requires an appropriate supply of nutrients, particularly nitrogen, phosphorus, and potassium, for improved and sustained yield (Asghar et al., 2010; Banerjee et al., 2014). In modern hybrid maize, nitrogen (N), phosphorus (P), and potassium (K) play key roles in plant growth and development, chloroplast synthesis, protein synthesis (Jordan-Meille and Pellerin 2008; Bukhsh et al., 2012), and nutrient translocation and utilization (Minjian et al., 2007). The optimum amount of the elements in the soil cannot be used efficiently if these nutrients are deficient in plants. Maize crop response to nutrients varies greatly depending on soil and environmental conditions. The efficiency of nutrient usage increased until a certain amount of fertilizer application was reached, then curved as fertilizer application was increased further (Rehman et al., 2011). Improving nutrient efficiency is a noble goal and a serious challenge for the fertilizer industry and agriculture as a whole. To maximize crop yields and nutrient use efficiency, knowledge of the optimum fertilizer rate and crop nutrient requirements is essential for the benefits of the farmers and the environment.

Nutrient and its use efficiencies are the most significant constraint to increasing maize productivity. The partial factor productivity (PFP), partial nutrient budget (PNB), internal efficiency (IE), physiological efficiency (PE), recovery efficiency (RE), and agronomic efficiency (AE) of applied nutrients used to estimate nutrient use efficiencies (NUE) are commonly used in agronomic studies (Dobermann 2007; Snyder and Bruulsema 2007; Liu et al., 2011; Ray et al., 2017). To enhance both maize productivity and the environment, more effective N fertilizer use is required (Huang et al., 2018). Phosphorus deficiency in the soil decreases the nitrogen use efficiency (Delve et al., 2009). The use of K enhanced N absorption, resulting in a higher NUE (Brar et al., 2011). With reports averaging 33% of fertilizer nitrogen (N) recovered by the crop, the NUE for world cereal production is poor (Raun and Johnson 1999). Just 30–50% of applied nitrogen fertilizers (Smil 2002; Ladha et al., 2005) and 45% of applied phosphorus fertilizers (Smil 2000) are estimated to be used for crops today. In the same way, fertilizer N recovery for corn might reach 65 percent (Ladha et al., 2005).

Phosphorus use efficiency in maize fields is crucial, as this nutrient is one of the most production-limiting elements (Coelho et al., 2008). Even if P is present in higher concentrations in soil, plant availability is often hampered due to the phosphate binding capacity of various soil types (Syers et al., 2008). Around 90% of added fertilizer phosphorus is fixed in acidic soil containing iron and aluminum, making it inaccessible to plants (Potash and Phosphate 2003). Phosphorus use efficiency can range from 90% in well-managed agroecosystems (Syers et al., 2008) to 10–20% in highly phosphorus-fixing soils (Bolland and Gilkes 1998). Most agricultural crops recover 20-30% of applied P and in crops grown in soil with low potassium reserves, a realistic target of 40-60% potassium recovery efficiency has been reported under favorable conditions (Dobermann 2007). In cereal crops, global P use efficiency was reported to be only 16 % (Dhillon et al., 2017). Most farmers in this region do not use mineral fertilizers, especially K fertilizers, and as a result, crop do not receive the sufficient nutrients they need for proper growth and grain production.

Although the maximum nutrient use efficiency is usually found at the lower parts of the yield response curve, where fertilizer inputs are lowest, fertilizer efficacy in increasing crop yields and optimizing farmer profitability should not be compromised purely for efficiency's sake (Ghosh et al., 2015). It's critical to find a balance between crop productivity and nutrient efficiency. In order to minimize losses and achieve better fertilizer practices, the variables considered in optimizing the use of nutrients, such as the correct dose, should be evaluated and examined (Fixen, 2010). The objective of this research was to evaluate how various levels of nitrogen, phosphorus, and potassium affected grain yield and NPK use efficiency in hybrid maize which helps to maximize the management practices for achieving higher yield.

Materials and Methods

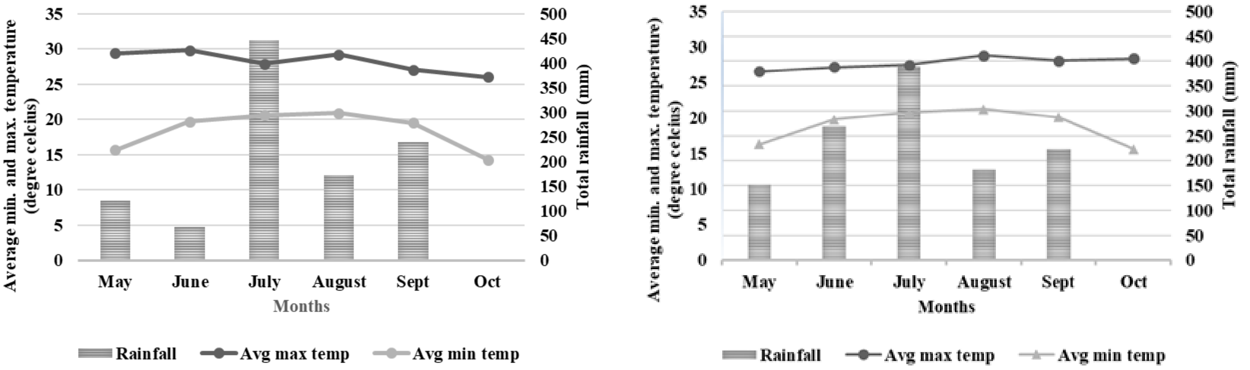
Experimental Site

Field experiments were carried out during the monsoon seasons of 2019 and 2020 at National Agronomy Research Center and laboratory analysis and laboratory work was performed at National Soil Science Research Center, Khumaltar, Lalitpur, which situated in mid hill valley condition of Nepal (27°39’ North latitude, 85°19’ East longitude, 1285 above mean sea level). In the first season, meteorological data shows the highest monthly average maximum temperature of 29.7°C was faced by crop in June, 2019 that coincided with V6 to V8 stage of maize and the lowest temperature was 14.3°C in October, 2019. Similarly, in the second season, the highest average maximum temperature of 28.8°C was faced by maize crop during August, 2020 which coincided with silking to grain filling stage and the lowest average temperature was 15.7°C in October, 2020. Likewise, the precipitation of 1043.3 mm and 1149.6 mm was received by the first and the second maize crop, respectively which falls in month of July and coincided tasseling and silking stage of maize. The agrometeorological data were collected from National Agronomy Research Center, Khumaltar, Lalitpur, Nepal (Figure 1).

Before the field experiment, the soil in the experimental plot had a pH of 5.98 (acidic) and contained low organic matter (2.01%), medium total nitrogen (0.14%), high available phosphorus (478.6 kg ha^{-1}) and medium available potassium (160.5 kg ha^{-1}). With a silty clay loam soil texture, the average bulk density was 1.39 gm cm^{-3}. To evaluate the fertility status, the soil was rated using Khatri Chhetri's (1991) soil value chart.

Experimental Setup and Treatments

The experiment was laid out in three factorial randomized complete block design (RCBD) consisting 27 treatments and three replications. The three factors consist three levels of nitrogen (150, 180 and 210 kg ha^{-1}), three levels of phosphorus (40, 60 and 80 kg ha^{-1}) and three levels of potassium (40, 60 and 80 kg ha^{-1}) containing of 81 plots. Three nutrient omission treatments (-N, -P, and -K) of three replications were also included in the treatments to determine NUE. Individual plots size comprised of 10.5 m^2 (4.2 m × 2.5 m). Between two plots, a 0.7 m bunding was done, and the replication was separated by 1 m.



(a) 2019

(b) 2020

Figure 1. Average monthly maximum and minimum temperature and rainfall during crop growing seasons in the study site

Crop Management

On the 9th of May, 2019 and the 15th of May, 2020, maize seed was sown in well-prepared plots at a spacing of 60 × 25 cm, with two seeds per hill. Khumal Hybrid-2 was the hybrid maize variety used in the experiment. The fertilizers used to supply nitrogen, phosphorus, and potassium were urea (46% N), single super phosphate (16% P_2O_5), and muriate of potash (60% K_2O). Phosphorus and potassium fertilizers were applied in full doses during land preparation while nitrogen was applied in three stages: 1/3 as a basal application, 1/3 at 30-35 days after sowing, and 1/3 at the tasseling stage of maize during both seasons. When the crop reached a height of 15 cm, it was thinned to keep one plant per hill. To check weed-crop competition, the plot was hoed twice: once at knee height and again before tasseling. Furthermore, during different stages of maize development, all required agronomic practices were carried out consistently as required homogenously with proper care. Insecticides Fauji (Fipronil 0.3% GR) @15 kg/ha was used at the time of field preparation followed by spraying G-Sunami (Chlorpyrifos 50% + Cypermethrin 5% EC) @1ml/L to control cutworms. To control American Armyworm, Spinosad 45% EC@0.3 ml/L (20 and 40 days after sowing) and Chlorantraniliprole 18.5 % w/w @0.4 ml/L (30 days after sowing) were applied alternately thrice during the crop season. For weed management, Atrazine 50% WP @1.0 kg a.i/ha (4 g/litre of water) was used as a pre-emergence treatment two days after sowing and Tembotrione 75% EC @120 g a.i/ha (4 ml/litre of water) was used as a post-emergence treatment at 25 days after sowing. On September 22nd, 2019 and September 28th, 2020, the crop was manually harvested.

Plant Sampling and Analysis

Grain yield was measured on a subplot basis using a net plot area of 5.25 m^2, adjusted for moisture content at 14%, and converted to tons per hectare. Six plant samples (leaves, stem, tassel and husk) from net plot harvest were collected randomly at maturity of maize to make a composite sample and washed with tap water and then distilled water to extract adhering soil and dust. The grains were deshelled from six cobs and made a composite sample. The plant samples were oven dried at 70°C until constant weights were obtained, then grinded to a fine powder that passes through 0.2 mm sieve, and placed in polythene bags. The grain and stover samples were digested in di-acid of concentrated nitric acid (HNO_3) and hydrogen per oxide (H_2O_2). Nitrogen was determined using Kjeldahl's digestion-distillation method (Bremner 1996), while P_2O_5 and K_2O were estimated using Vanadate-Molybdate-phosphoric yellow color method and flame photometer method (Jackson 1973) from an extract prepared from digestion of acids. The nutrient accumulation in the above ground parts of the plant was calculated in kg ha^{-1}.

Nutrient Use Efficiency Indices Calculation

The PFP is measured in terms of crop yield per unit of nutrient applied. The PNB is expressed in terms of nutrient uptake by the harvested part per unit of nutrient added and is used to assess the long-term viability of a cropping system following Snyder and Bruulsema (2007). The amount of grain yield produced per kilogram of nutrient accumulation in above-ground plant dry matter is expressed as internal efficiency. The physiological efficiency is defined as the ratio of kg grain production to kg nutrient uptake in above-ground dry matter production. The increase in crop uptake of a nutrient in the above-ground portions of the plant in response to application of that nutrient is described as recovery efficiency. Agronomic efficiency is measured in terms of increased grain yield per unit of applied nutrient. The PE, PNB, IE, PE, RE, and AE were estimated using Dobermann (2007), Ray et al., (2017) and Liu et al., (2011) equations, as follows:

$$\text{TNU}=(\text{GY}\times\text{NC})+(\text{SY}\times\text{NCS})$$

$$\text{PFP}_X = \text{Grain yield } F_A/\text{Fertilizer applied} \qquad (1)$$

$$\text{PNB}_X = \text{Total nutrient uptake } F_A/\text{Fertilizer applied} \qquad (2)$$

$$\text{IE}_X = \text{Grain yield } F_A \,/\, \text{Total nutrient uptake } F_A \qquad (3)$$

$$\text{PE}_X=\frac{(\text{GY } F_A - \text{GY } F_0)}{(\text{TNU } F_A - \text{TNU } F_0)} \qquad (4)$$

$$\text{RE}_X=\frac{(\text{TNU } F_A - \text{TNU } F_0)}{\text{FA}}\times 100 \qquad (5)$$

$$\text{AE}_X=\frac{\text{GY } F_A - \text{GY } F_0}{\text{FA}} \qquad (6)$$

Where
TNU= Total Nutrient uptake
GY = Grain yield (kg ha^{-1})
NC = Nutrient concentration (%) in grain
SY = Straw yield (kg ha^{-1})
NCS = Nutrient concentration (%) in straw
FA = Fertilizer applied

X= N, P, and K; F_A=with fertilizer; F_0=without fertilizer, PFP, PNB, IE, PE, AE are expressed in kg kg^{-1} whereas RE is expressed in percentage. All the applied fertilizers, yield of grain, total nutrient uptake is expressed in kg.

Statistical Analysis

Grain yield as well as NUE indices were calculated as the average for the years 2019 and 2020. Data were subjected to analysis of variance (ANOVA) to evaluate the significance of treatment effect as given by Gomez and Gomez (1984). Means were compared by Duncan's Multiple Range Test (DMRT) at 5% level of significance (Steel 1997)). The graphs were created using Microsoft Excel and Sigma plot software (version 12.0).

Results

Maize Yield

The two-year average results show that N 210 kg ha^{-1} (10.95 t ha^{-1}) and K_2O 80 kg ha^{-1} (10.54 t ha^{-1}) produced significantly higher grain yields followed by N180 (9.77 t ha^{-1}) and K_2O 60 kg ha^{-1} (9.99 t ha^{-1}), respectively (Figure 2). The lowest grain yield of 9.21 t ha^{-1} and 9.39 t ha^{-1} was produced by N 150 kg ha^{-1} and K_2O 40 kg ha^{-1}. However, there was no substantial phosphorus response beyond 40 kg P_2O_5 kg ha^{-1}.

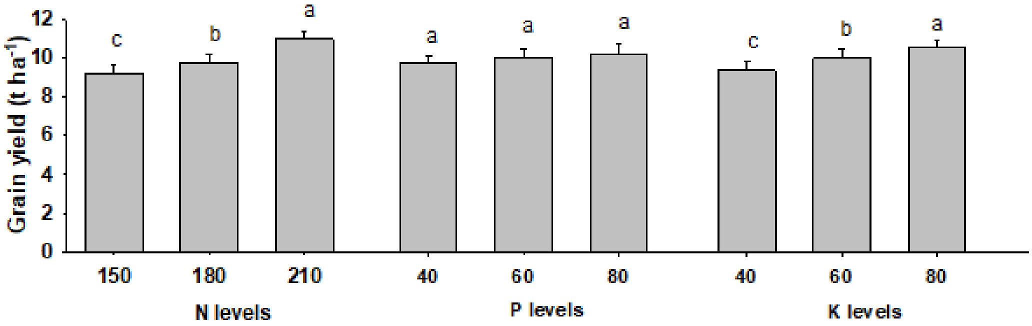


Figure 2. Grain yield of maize as affected by NPK levels (2019-2020).

Different small alphabetical letters indicate significant differences at $P<0.05$ (otherwise statistically at par). Bars indicate mean with standard error.

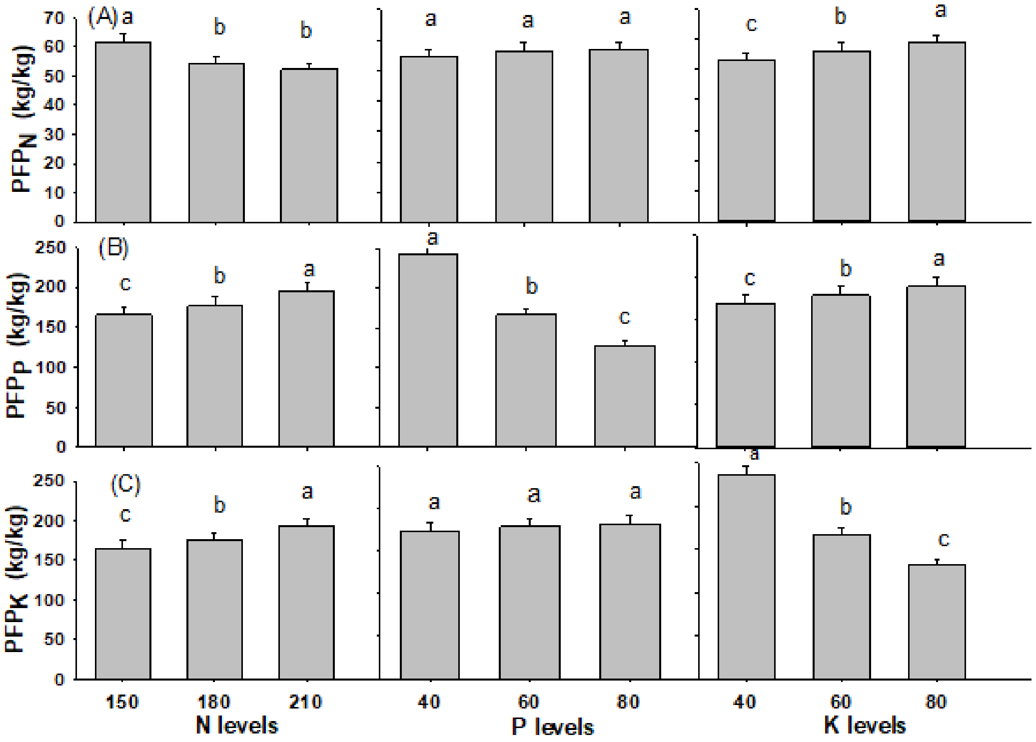


Figure 3. Partial factor productivity of hybrid maize (A) nitrogen (B) phosphorus (C) potassium as influenced by different levels of NPK fertilizer (2019-2020).

Different small alphabetical letters indicate significant differences at $P<0.05$ (otherwise statistically at par). Bars indicate mean with standard error.

The interaction of N × P was found to be significant while all the other interactions: N × K, P × K and N × P × K was found to be non-significant on grain yield of maize (Table 1).

Partial Factor Productivity

The significantly higher PFP_N (61.4 kg kg^{-1}) of maize was recorded with the application of N 150 while the lowest (52.1 kg kg^{-1}) was observed from the application of N 210 kg ha^{-1} (Figure 3). With the higher P_2O_5 and K_2O application rate of 80 kg ha^{-1} each, higher PFP_N (59.9 and 59.0 kg kg^{-1}, respectively) were recorded while it decreased with decreasing nutrient rates. At the same time, the higher PFP_P (194.8 kg kg^{-1}) and PFP_K (194.2 kg kg^{-1}) were observed with the application of N 210 kg ha^{-1} whereas lower values were recorded from low rates showing similar trends as that of PFP_N. The maximum PFP_P was recorded by the use of P_2O_5 40 kg ha^{-1} (242.7 kg kg^{-1}) and K_2O 80 kg ha^{-1} (181.7 kg kg^{-1}) while the lowest value was obtained with the application of P_2O_5 80 kg/ha (127.8 kg kg^{-1}) and K_2O 40 kg/ha (173.0 kg kg^{-1}). Similarly, significantly higher PFP_P (189.3 kg kg^{-1}) and PFP_K (234.9 kg kg^{-1}) of hybrid maize was recorded with the application of P_2O_5 80 kg ha^{-1} and K_2O 40 kg ha^{-1} while the lowest (169.0 kg kg^{-1} and 131.8 kg kg^{-1}) were observed from the application of P_2O_5 40 kg ha^{-1} and K_2O 80 kg ha^{-1}, respectively.

Partial Nutrient Budget

Effect of nitrogen levels on PNB_N of maize was significantly higher (0.98 kg kg^{-1}) from the application of N 150 kg ha^{-1} and the lowest (0.95 kg kg^{-1}) was obtained from N 210 kg ha^{-1} (Figure 4). However, the higher PNB_N of 0.99 kg $kg^{-1}$and 1.03 kg kg^{-1}were recorded by the use of P_2O_5 80 kg ha^{-1} and K_2O 80 kg ha^{-1}, respectively while the lowest value of 0.9 kg kg^{-1} and 0.86 kg kg^{-1} were observed from the application of P_2O_5 40 kg ha^{-1} and K_2O 40 kg ha^{-1}. Similarly, significantly higher PNB_P (2.07 kg kg^{-1} and 1.97 kg kg^{-1}) was recorded with the application of N 210 kg ha^{-1} and K_2O 80 kg ha^{-1}, respectively while the lowest of 1.59 kg kg^{-1}and 1.648 kg kg^{-1} were observed from the application of N 150 kg ha^{-1} and K$_2$O 40 kg ha^{-1}, respectively. Higher value of PNB$_P$ (2.37 kg kg^{-1}) was recorded with the application of P$_2$O$_5$ 40 kg ha^{-1} and while the lowest (1.35 kg kg^{-1}) was observed from application of P$_2$O$_5$ 80 kg ha^{-1}.

At the same time, significantly greater value of PNB$_K$ (1.89 kg kg^{-1}and 1.73 kg kg^{-1}) in maize was reported with the application of N 210 kg ha^{-1} and P$_2$O$_5$ 80 kg ha^{-1} while the smallest value of 1.44 kg kg^{-1}and 1.54 kg kg^{-1} were found from the application of N@150 kg ha^{-1} and P$_2$O$_5$ 40 kg ha^{-1}, respectively. The effect of K levels on maize PNB$_K$ was significantly higher (2.1 kg kg^{-1}) when K$_2$O 40 kg ha^{-1} was applied, and was the lowest (1.29 kg kg^{-1}) when K$_2$O 80 kg ha^{-1} was applied.

Internal Efficiency

The significantly higher IE$_N$ (63.1 kg kg^{-1}, 60.9 kg kg^{-1}and 61.5 kg kg^{-1}) was recorded with the application of N 150 kg ha^{-1}, P$_2$O$_5$ 40 kg ha^{-1} and K$_2$O 40 kg ha^{-1}, respectively while the lowest values were observed from the application of N 210 kg ha^{-1}, P$_2$O$_5$ 80 kg ha^{-1} and K$_2$O 80 kg ha^{-1} (55.4 kg kg^{-1}, 57.6 kg kg^{-1} and 57.7 kg kg^{-1}, respectively) (Figure 5). The application of N 150 kg ha^{-1}, P$_2$O$_5$ 40 kg ha^{-1} and K$_2$O 40 kg ha^{-1} resulted in the higher IE$_P$ (102.2 kg kg^{-1}, 102.2 kg kg^{-1} and 100.9 kg kg^{-1}) while the lowest value of IE$_P$ (94.2 kg kg^{-1}, 94.1 kg kg^{-1} and 95.8 kg kg^{-1}) was found from the application of N 210 kg ha^{-1}, P$_2$O$_5$ 80 kg ha^{-1} and K$_2$O 80 kg ha^{-1}, respectively, in Khumal hybrid-2 maize.

Similarly, higher IE$_K$ (118.0 kg kg^{-1}, 119.0 kg kg^{-1} and 120.9 kg kg^{-1}) was recorded with the application of N 150 kg ha^{-1}, P$_2$O$_5$ 40 kg ha^{-1} and K$_2$O 40 kg ha^{-1}, respectively while the lowest value of 108.1 kg kg^{-1}, 107.7 kg kg^{-1} and 107.9 kg kg^{-1} were observed from the application of N 210 kg ha^{-1}, P$_2$O$_5$ 80 kg ha^{-1} and K$_2$O 80 kg ha^{-1}, respectively.

Physiological Efficiency

The significantly higher PE$_N$ (46.2 kg kg^{-1}) was obtained with the application of N 150 kg ha^{-1} and the lowest were found with the application of N 210 kg ha^{-1} (40.3 kg kg^{-1}) whereas the application of P and K rates were found to be non-significant on PE$_N$ (Figure 6). The maximum PE$_N$ (45.4 kg kg^{-1} and 45.1 kg kg^{-1}) were recorded with the application of P$_2$O$_5$ 40 kg ha^{-1} and K$_2$O 40 kg ha^{-1}, respectively while the lowest PE$_N$ (41.8 kg kg^{-1} and 42.3 kg kg^{-1}) was observed from the application of P$_2$O$_5$ 80 kg ha^{-1} and K$_2$O 80 kg ha^{-1}.

Similarly, application of N 150 kg ha^{-1}, P$_2$O$_5$ 40 kg ha^{-1} and K$_2$O 40 kg ha^{-1} resulted the higher PE$_P$ (115.6 kg kg^{-1}, 119.9 kg kg^{-1} and 111.1 kg kg^{-1}, respectively) whereas the lowest PE$_P$ (94.3 kg kg^{-1}, 79.9 kg kg^{-1} and 101.9 kg kg^{-1}) was observed with N 210 kg ha^{-1}, P$_2$O$_5$ 80 kg ha^{-1} and K$_2$O 80 kg ha^{-1}. The maize plant recorded the greater value of PE$_K$ with the use of N 150 kg ha^{-1} (156.4 kg kg^{-1}), P$_2$O$_5$ 40 kg ha^{-1} (161.1 kg kg^{-1}) and K$_2$O 40 kg ha^{-1} (161.2 kg kg^{-1}) while PE$_K$ of 117.7 kg kg^{-1}, 124.9 kg kg^{-1} and 122.5 kg kg^{-1} were recorded the lowest with the application of N 210 kg ha^{-1}, P$_2$O$_5$ 60 kg ha^{-1} and K$_2$O 80 kg ha^{-1}, respectively.

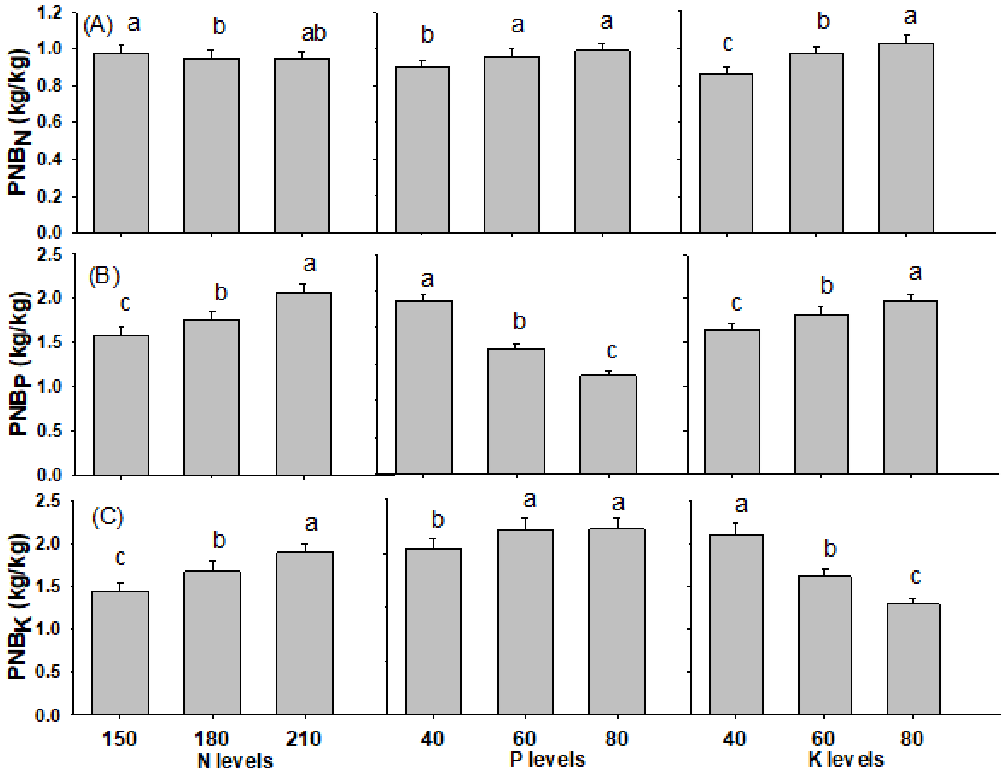


Figure 4. Partial Nutrient Budget of hybrid maize (A) nitrogen (B) phosphorus (C) potassium as influenced by different levels of NPK fertilizer (2019-2020).

Different small alphabetical letters indicate significant differences at $P<0.05$ (otherwise statistically at par). Bars indicate mean with standard error.

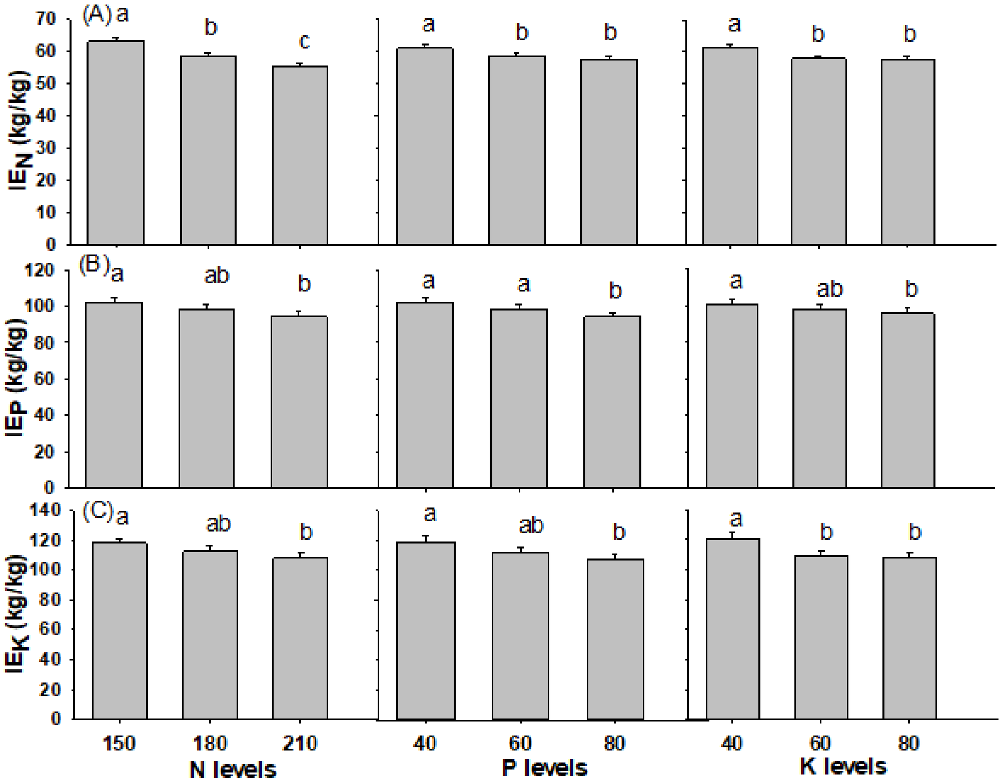


Figure 5. Internal Efficiency of hybrid maize (A) nitrogen (B) phosphorus (C) potassium as influenced by different levels of NPK fertilizer (2019-2020).

Different small alphabetical letters indicate significant differences at P<0.05 (otherwise statistically at par). Bars indicate mean with standard error.

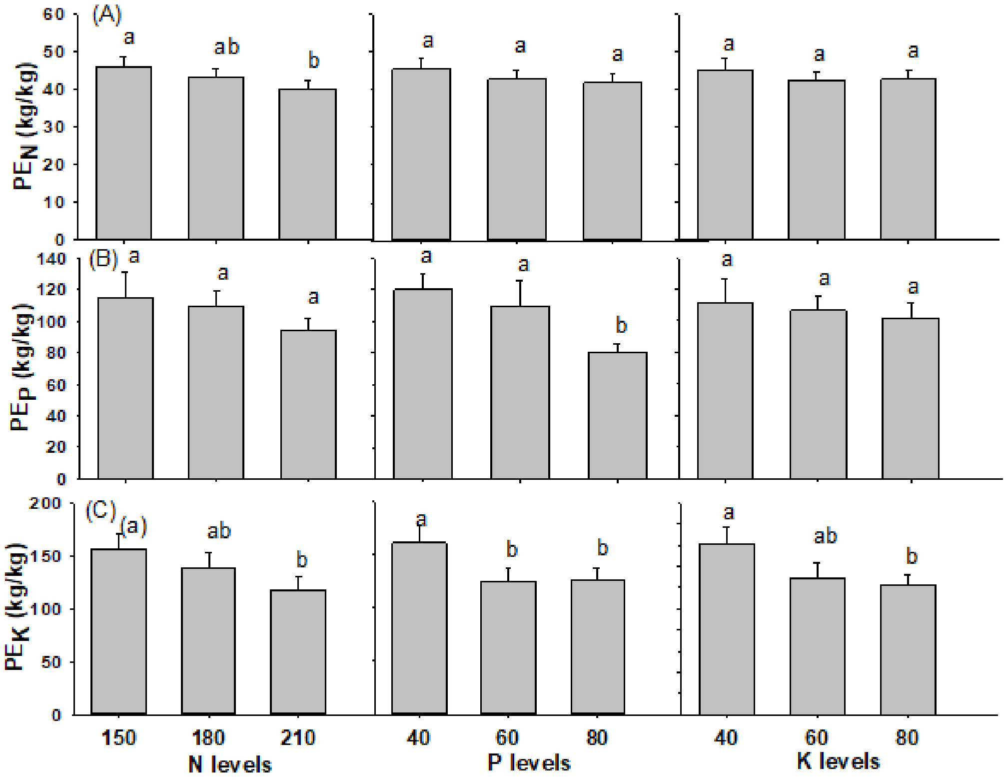


Figure 6. Physiological Efficiency of hybrid maize (A) nitrogen (B) phosphorus (C) potassium as influenced by different levels of NPK fertilizer (2019-2020).

Different small alphabetical letters indicate significant differences at P<0.05 (otherwise statistically at par). Bars indicate mean with standard error.

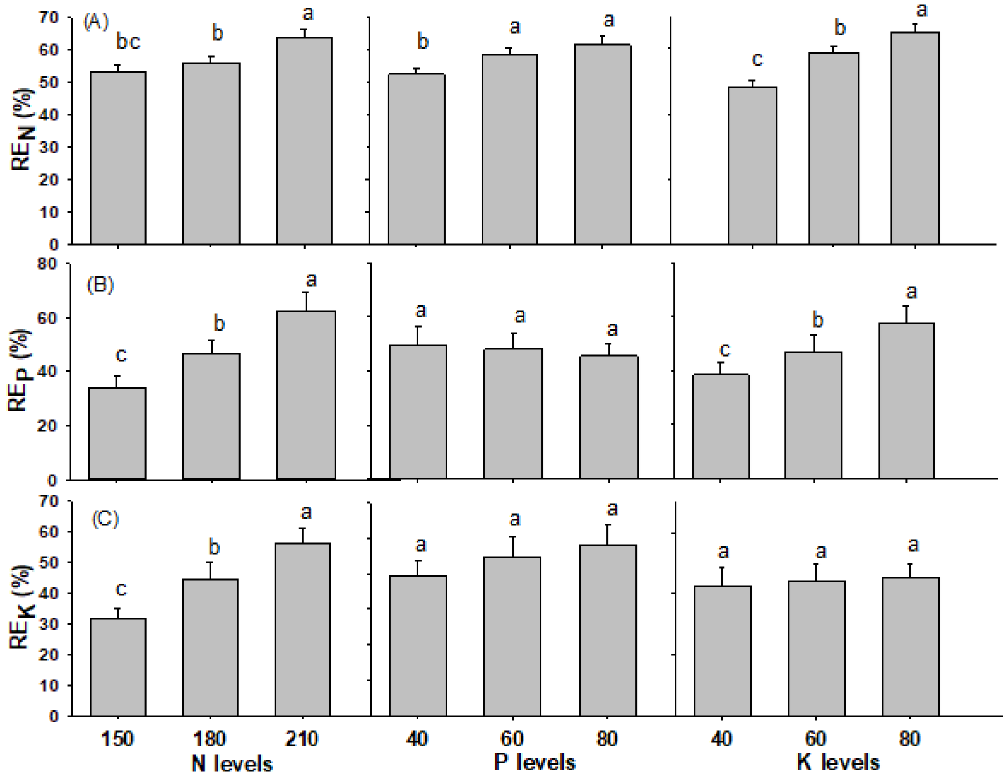


Figure 7. Recovery Efficiency of hybrid maize (A) nitrogen (B) phosphorus (C) potassium as influenced by different levels of NPK fertilizer (2019-2020).

Different small alphabetical letters indicate significant differences at $P<0.05$ (otherwise statistically at par). Bars indicate mean with standard error.

Recovery Efficiency

Maize showed the highest RE_N when N 210 kg ha^{-1}, P_2O_5 80 kg ha^{-1} and K_2O 80 kg ha^{-1} was applied (63.5%, 61.4% and 65.1%, respectively), while lowest value of 53.0%, 52.3% and 48.4% was obtained with the application of N 150 kg ha^{-1}, P_2O_5 40 kg ha^{-1} and K_2O 40 kg ha^{-1} (Figure 7). Similarly, higher RE_P of 76.8% with application of 210 kg N ha^{-1}, 57.0% with application 40 kg P_2O_5 ha^{-1} and 66.4% with the application of 80 kg K_2O ha^{-1} was obtained whereas the lower value of RE_P was recorded with the application of N 150 kg ha^{-1}, P_2O_5 40 kg ha^{-1} and K_2O 40 kg ha^{-1} (29.7%, 45.0% and 34.8%, respectively).

With the use of N 210 kg ha^{-1}, P_2O_5 80 kg ha^{-1} and K_2O 60 kg ha^{-1}, higher RE_K of 65.6%, 53.5% and 46.8%, respectively were obtained whereas the lowest value of 24.9%, 33.6% and 43.8% were observed with the application of N 150 kg ha^{-1}, P_2O_5 40 kg ha^{-1} and K_2O 40 kg ha^{-1}, respectively.

Agronomic Efficiency

The hybrid maize recorded higher AE_N of 25.3 kg kg^{-1}, 25.0 kg kg^{-1} and 27.1 kg kg^{-1} with the application of N 210 kg ha^{-1}, P_2O_5 80 kg ha^{-1} and K_2O 80 kg ha^{-1} while the lowest was observed from the application of N 150 kg ha^{-1} (23.0 kg kg^{-1}), P_2O_5 40 kg ha^{-1} (22.6 kg kg^{-1}) and K_2O 40 kg ha^{-1} (20.9 kg kg^{-1}) (Figure 8). The application of N 210 kg ha^{-1}, P_2O_5 40 kg ha^{-1} and K_2O 80 kg ha^{-1} resulted in the higher AE_P of 61.2 kg kg^{-1}, 57.7 kg kg^{-1} and 55.7 kg kg^{-1}, respectively, while the lowest values of AE_P (31.9 kg kg^{-1}, 35.2 kg kg^{-1} and 35.4 kg kg^{-1}) were found from the application of N 150 kg ha^{-1}, P_2O_5 80 kg ha^{-1} and K_2O 40 kg ha^{-1}, respectively.

At the same time, the higher AE_K (65.0 kg kg^{-1}, 52.4 kg kg^{-1} and 55.9 kg kg^{-1}) were obtained with the application of N 210 kg ha^{-1}, P_2O_5 80 kg ha^{-1} and K_2O 40 kg ha^{-1}, respectively whereas lower values were observed from N 210 kg ha^{-1} (35.4 kg kg^{-1}), P_2O_5 40 kg ha^{-1} (43.8 kg kg^{-1}) and K_2O 80 kg ha^{-1} (48.3 kg kg^{-1}).

The interactions of N × P, N × K, P × K and N × P ×K on PFP, IE, PNB, RE, AE and PE in maize crop are presented in Table 1.

Discussion

Nutrients and Grain yield

Maize is grown in the mid-hills of Nepal during the monsoon season, when the amount and intensity of rainfall is high. The loss of nutrients by leaching is normal in areas with high rainfall. According to Thomison et al., (2004), excessive rainfall after planting often results in N loss through denitrification and leaching. The loss of nutrients reduces the maize production system's nutrient use efficiency, resulting in lower grain yields (Tadesse et al., 2013). Since fertilizer is relatively expensive when compared to produce, effective N fertilizer use is important for both agroeconomic and environmental reasons (Nyamangara et al., 2003). Fertilizer should be applied at the prescribed rate for optimum efficiency and productivity. Baral *et al*, 2020 observed encouraging results on hybrid maize (Khumal Hybrid-2) in Western Nepal that mostly focused on N application method. Their research results showed that deep placement of urea briquettes was found to be economic and it could replace 25% of N compared to the recommended practice.

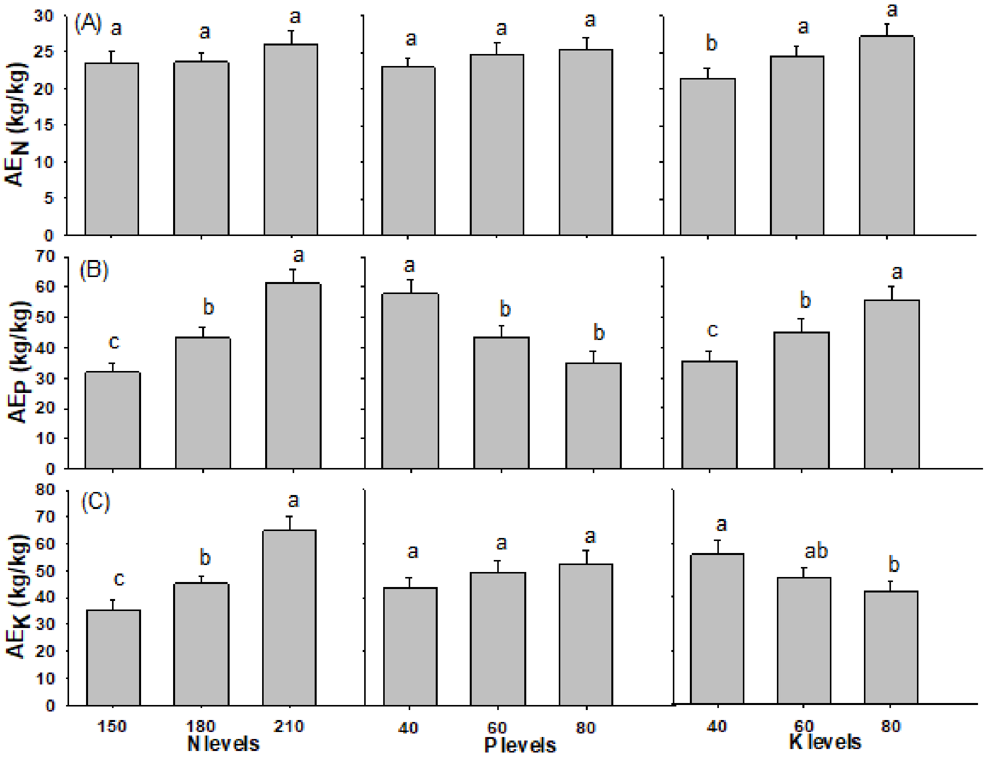


Figure 8. Agronomic Efficiency of hybrid maize (A) nitrogen (B) phosphorus (C) potassium as influenced by different levels of NPK fertilizer (2019-2020).

Different small alphabetical letters indicate significant differences at $P<0.05$ (otherwise statistically at par). Bars indicate mean with standard error.

Table 1. Summary of analysis of variance (ANOVA) of F test Probability (P>F) (pooled data of two years)

S.N	Parameters	Nutrient	N	P	K	N × P	N × K	P × K	N × P × K
1	Grain yield		***	NS	**	NS	NS	NS	NS
2	PFP	N	***	NS	**	**	NS	NS	NS
		P	***	***	***	**	NS	NS	NS
		K	***	NS	***	**	NS	NS	NS
3	IE	N	***	**	***	NS	NS	NS	NS
		P	***	**	*	**	NS	NS	NS
		K	*	*	*	NS	NS	NS	NS
4	PNB	N	*	**	**	**	NS	NS	NS
		P	***	***	***	NS	NS	NS	*
		K	***	*	***	*	NS	NS	NS
5	RE	N	***	**	***	***	NS	NS	**
		P	***	NS	***	*	NS	NS	*
		K	***	NS	NS	NS	NS	NS	NS
6	AE	N	NS	NS	**	**	NS	NS	NS
		P	***	**	***	**	NS	NS	NS
		K	***	NS	*	**	NS	NS	NS
7	PE	N	**	NS	NS	NS	NS	NS	NS
		P	NS	**	NS	*	NS	NS	*
		K	*	*	*	NS	NS	NS	NS

NS=non-significant (P>-0.05); ***=significant at 0.1%; *=significant at 1% and *=significant at 5%

The grain yield was influenced by N and K levels for two years, with an average of 9.98 ton/ha. Similar to our findings, Rutkowska et al., (2014) discovered that combining K fertilizer with nitrogen fertilization in the range of 150–250 kg N/ha resulted in a 9 t/ha corn yield. The level of nitrogen supply influences the yield response to potassium fertilization to a large extent (Brennan and Bolland 2009). Enhanced nitrogen and potassium application increased nutrient availability in the soil and nitrogen and potassium uptake in the maize plant, resulting in an increase in maize grain production. And that might be the reason why the grain yield of Khumal Hybrid-2 was maximum when N was at 210 kg ha^{-1} and K_2O was at 80 kg ha^{-1}. However, due to higher P availability in the soil, there was no significant increase of phosphorus beyond 40 kg P_2O_5 kg ha^{-1}. It may be the result of carryover effects of residual P from previous P fertilizer applications before planting. Increased nitrogen rates increased maize grain yield, according to Seadh et al., (2013) and Adhikary and Adhikary (2013). K treatment enhanced grain production due to improvements in prolificacy and grain weight, according to Ahmad et al., (2009) and Liaqat et al., (2018).

Partial Factor Productivity

The partial factor productivity index is a reliable way to compare the economic benefits of fertilization in different areas. PFP_N was higher when N application rates were low and it decreased as N levels increased, similar to findings of Khalili et al., (2018), but it increased with increased in PK levels and vice versa. In the case of PFN_P and PFP_K, a similar pattern was observed which is in agreement with that of Ray et al., (2017). Variations in average PFP between regions rely on yield potential, soil quality, amount and form of fertilizer application and other crop management operations including overall timeliness and quality, according to Dobermann and Cassman (2005). On average, PFP_N (55.9 kg kg^{-1}), PFP_P (179.1 kg kg^{-1}) and PFP_K (177.7 kg kg^{-1}) observed in our study was within the benchmarks (40-90 kg kg^{-1}, 100-250 kg kg^{-1} and 75-200 kg kg^{-1}, respectively) documented by Fixen et al., (2015). The average PFP_N in our study is similar to the value of 62 kg kg^{-1} recorded by Baral et al., (2020), the value of 63.0 kg kg^{-1} observed by Xu et al., (2017), and the value of PFP_N >60 kg kg^{-1} obtained by Dobermann (2007) in well managed systems. These findings support those of Sharifi and Namvar (2016), and Nemati and Sharifi (2012), who found that increasing fertilizer rates decreases NUE because yield rises slower than N supply in soil and fertilizer.

Partial Nutrient Budget

PNB_N, PNB_P, and PNB_K were higher when corresponding N, P, K application rates were low and decreased as nutrient levels increased with the mean values 0.95 kg kg^{-1}, 1.81 kg kg^{-1} and 1.67 kg kg^{-1}, respectively. These values were higher than the benchmarks values of 0.7-0.9 kg kg^{-1} as recorded by Fixen et al., (2015). PNB values greater than one signifies the requirement for fertility replenishment from N, P, and K fertilization as suggested by Ray et al., (2017). Snyder and Bruulsema (2007) recommended that PNB is >1 in nutrient-deficient systems (fertility improvement), <1 in nutrient-surplus systems (under-replacement), and is significantly less than 1:1 in sustainable systems. Our findings showed that amount of nutrient uptake was higher than the amount of nutrient supplied through fertilizer in case of P and K which might not be sustainable system. Improvement of nutrient through application of additional fertilizer and decreasing the loss of nutrient through management practices should be done to make it sustainable.

Internal Efficiency

Internal efficiency is a measurement of a plant's ability to convert nutrients from all sources (soil and fertilizer) into economic yield (grain) as described by Liu et al., (2011). A low IE indicates that internal nutrient conversion is poor and vice-versa. IE_N ranged from 55.4 to 63.1 kg kg^{-1}, with a mean of 59.1 kg kg^{-1}, which is within the range of IE reported by Pathak et al., (2003) in cereal-based systems (18.3-65.9 kg kg^{-1}), similar to the optimal range of IE_N (55 to 65 kg kg^{-1}) for balanced nutrition at higher yield as recorded by Dobermann (2007) and higher than average IE_N (44.4 kg kg^{-1}) recorded by Xu et al., (2017). The IE_P averaged 98.24 kg kg^{-1} and IE_K averaged 112.8 kg kg^{-1} in hybrid maize in mid hill condition.

Physiological Efficiency

The increase in yield in proportion to the change in crop uptake of the nutrient in above-ground sections of the plant is expressed as PE. It's similar to AE and RE. On average, PE_N of 43.28 kg kg^{-1}, PE_P of 106.5 kg kg^{-1} and PE_K of 137.5 kg kg^{-1} were observed in our study in which PE for all the three nutrients were poor for the treatments where N, P and K application was high and vice-versa. The low PE indicates that accumulation of nutrients (input) was higher than the grain yield (output). Amado et al., (2017) observed PE_N was higher when N application rates were low and it decreased as N levels increased, similar to our findings. The researchers recorded PE_N value of 40 kg kg^{-1} from the application of N@180 kg ha^{-1}, which is comparable to our report, which obtained PE_N value of 43.4 kg kg^{-1} at the same rate of nitrogen application. The PE_N obtained in our study was same as maximum PE_N (42.95 kg kg^{-1}) observed by Niaz et al., (2015) and greater than the value of 37 kg kg^{-1} published by Ladha et al., (2005) and maximum value of 31.63 kg kg^{-1} recorded by Goshu et al., (2019).

Recovery Efficiency

Despite the fact that large quantities of N fertilizers were used all over the world, crop recovery or efficiency of N fertilizers in agricultural production is poor, ranging from 25% to 50% of the applied N (Chien et al., 2016; Dobermann et al., 2003). Excessive rainfall occurred during maize season might have caused nitrate leaching or denitrification, which may be the primary cause of N loss. The RE_N, RE_P, and RE_K values of 57.4, 50.7%, and 44.0% falls within the range of RE obtained (31.2% to 105.6%) by Ray et al., (2017), and Fosu-Mensah and Mensah (2016) observed RE_N ranged from 23.5 to 73.1% during their experiment in maize crop. In this experiment, mean RE_N was found to similar to previous studies recorded by Ladha et al., (2016) who recorded the highest value of RE_N (57% of the crop N harvest) in maize among the cereals and higher than the target value of 50% suggested by Dobermann (2007). The relatively higher values of RE might be due to residual nutrients from previous crops and soil indigenous nutrient supply. The higher the rate of N application, higher was the uptake of N by the crop, therefore high value of RE_N was observed with high level of nitrogen which is in the line with Keeney (1982) who observed that NUE was increased by providing as much nitrogen as the crop needs. RE_P and RE_K of hybrid maize decreased with further addition of P and K which might be because of diminishing returns. Smil (2000) documented that 45% of P fertilizer is taken up by the crops, similar to our average RE_P in maize plant. The range of RE_K recorded in our study correlates the findings of Ghosh et al. (2015) in which the amount of applied K recovered in the first year can range from 20% to 60%.

Agronomic Efficiency

Agronomic efficiency which indicates how much yield is enhanced for additional unit of nutrients. The AE_N, AE_P and AE_K affected by the NPK levels ranged from 23.0 to 27.2 kg kg^{-1}, 31.9 to 61.2 kg kg^{-1} and 35.4 to 65.0 kg kg^{-1} with the mean value of 24.4, 45.4 and 48.5 kg kg^{-1}, respectively. AE_N measured in the current study is lower than the value (37 kg kg^{-1}) recorded by Duan et al., (2014) and similar to AE_N (24.7 kg kg^{-1}) recorded by Xu et al., (2017). Dobermann et al., (2007) suggested the target value (25 kg kg^{-1}) in maize who observed that the AE_N in cereals ranges from 10 to 30 kg kg^{-1} and can only be >30 kg kg^{-1} in well-managed systems with low N fertilizer amounts or a low soil N supply. Our findings are in agreement with that of Ray et al., (2017) found the AE_N varied from 5.6 to 23.6 kg kg^{-1} and Baral et al., (2020) recorded similar AE_N values of 30.2 kg kg^{-1}. The higher AE_P and AE_K with lower doses of P and K respectively were obtained in our study, similar to the findings of Xu et al., (2014). The higher the rate of N application, higher was the grain yield of the maize crop, therefore high value of AE_N was observed with high level of nitrogen. Similar to our finding, Khalili et al., (2018) and Niaz et al., (2015) recorded that higher the nitrogen rate, greater the AE_N. In the present study, the AE_P was poor for the treatments where N and K application were low and AE_K was low when N and P were used in lower rates. The results of this research as well as the findings of Kurwakumire et al., (2014) confirms that choosing a balanced fertilizer combination that attains the highest agronomic efficiency of each nutrient is critical.

It is appropriate to revise the dose of fertilizer as N 210 kg ha^{-1} and K_2O 80 kg ha^{-1} were optimum for higher maize production with grain yield of 10.95t/ha and 10.54 ton/ha, respectively in silty clay loam soil condition of mid hill of Nepal. The use of higher rate of inorganic P and K fertilizer improved the efficiencies of N by the maize and the case was also valid for efficiencies of P and K. N 150 kg ha^{-1} resulted the highest PFP_N, PNB_N, IE_N and PE_N whereas N 210 kg ha^{-1} showed the higher AE_N and RE_N. These findings can help to direct the use of chemical fertilizers in maize-based cropping systems thereby maintaining nutrient use efficiency. This form of research should be carried out in a variety of soil types, different varieties and agro-ecologies in order to establish a efficient nutrient management strategy in Nepal.

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Conflicts of Interest

The author declares no conflict of interest.

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