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# Alfalfa Response to Phosphorus and Potassium Fertility in Relation to Calcium and Magnesium

*Research Article*

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## Abstract

Balanced nutrition of phosphorus (P) and potassium (K) is needed for improving alfalfa (Medicago sativa L.) productivity. The relative levels of soil exchangeable calcium ($Ca^{+2}$) and magnesium ($Mg^{+2}$) to soil P and K levels can dictate alfalfa's response to P and K rates. Field and greenhouse experiments were conducted to determine alfalfa's response to P and K fertility relative to Ca and Mg levels. Treatments were

a) Field study: 10 selected combination rates (kg ha$^{-1}$) of three P (0, 34, and 67 $P_2O_5$), three K (0, 168, and 336 $K_2O$), two Ca (0 and 560 CaO), and two Mg (0 and 56 MgO).

b) Greenhouse study: 6 selected combination rates of two P (0 and 67 kg $P_2O_5$ ha$^{-1}$), two K (0 and 336 kg $K_2O$ ha$^{-1}$), three Ca (0, 4483, and 8967 kg CaO ha$^{-1}$), and three Mg (0, 448, and 897 kg MgO ha$^{-1}$).

Treatments were arranged under random complete blocks with three and six replications for field and greenhouse studies, respectively. The $P_{67}K_{336}$ treatment produced highest total annual forage yield either with $Ca_{560}Mg_{56}$ association (14.45 Mg ha$^{-1}$; 51% increase over the control) or without $Ca_{560}Mg_{56}$ association (13.80 Mg ha$^{-1}$; 44% increase over the control), under field conditions. Results from the greenhouse study showed that $P_{67}K_{336}$ treatment produces high yield response of alfalfa and the response declines with an increase in the relative levels of Ca and Mg. Alfalfa has shown significant yield response to P and K on soils with high exchangeable K, Ca and Mg levels. Growers are encouraged to consider the soil exchangeable levels of Ca and Mg relative to P and K from soil test results to improve decisions on P and K application rates for high alfalfa production.

**Keywords:** Alfalfa, Phosphorus, Potassium, Calcium; Magnesium; Yield Response

## Abbreviations

ADF: Acid Detergent Fiber; CP: Crude Protein; DM: Dry Matter; IVDMD: Invitro Dry Matter Digestibility; NDF: Neutral Detergent Fiber; NIRS: Near-Infrared Reflectance Spectroscopy; RFV: Relative Feed Value; TDN: Total Digestible Nutrient; SAREC: University of Wyoming James C. Hageman Sustainable Agriculture Research and Extension Center; LREC: University of Wyoming Laramie Research and Extension Center

## Core Ideas

a. Forage production of alfalfa heavily depends on phosphorus (P) and potassium (K) nutrients

b. Alfalfa's high demand of P and K requires the replenishment of P and K, and their influence on yield response when soil P and K levels are limiting

c. The proportions of exchangeable cationic nutrients such as $K^+$, calcium ($Ca^{+2}$) and magnesium ($Mg^{+2}$) can impact high yield production of alfalfa

d. Relative levels of exchangeable Ca and Mg to P and K levels should be considered to enhance plant available P and K for higher yield response

## Introduction

The positive relationship between improved alfalfa (Medicago sativa L.) production, phosphorus (P), and potassium (K) fertilization has been well documented [1-5]. Reports have shown increased forage yields of alfalfa following the application of P and K combination [6-9]. According to Craig [10], average yield of alfalfa consumes about 67kg P $ha^{-1}yr^{-1}$ and 224kg K $ha^{-1}yr^{-1}$ from the soil. The high requirement of P and K nutrients by alfalfa does not only necessitate replenishment of P and K to restore the soil nutrient levels, but to also ensure the crop's response to the applied nutrients to support increased yields in subsequent growing cycles. Thus, fertilizing alfalfa with a balanced of P and K (P × K) provides the plant with the needed essential nutrients to enhance its physiology, growth, and productivity.

In Indiana-USA, Berg et al. [11,12] found that alfalfa's long-term productivity can be increased by P and K fertilization, and therefore managing these nutrients to enhance their use efficiency by alfalfa is crucial for increasing forage yields and prolonging stand life. Improving the use efficiency of P and K for crop growth, requires enhanced acquisition by plants from the soil and enhanced utilization in processes that lead to faster growth and greater allocation of biomass. The use efficiency of applied P and K can vary with crop management system and location because crop response to fertilizer application depends on factors including soil status and soil nutrient availability [13,14]. The availability of soil nutrient is influenced by factors such as pH, moisture, texture, organic matter levels, and relative levels of other nutrients [15] and thus, application of P and K fertilizer nutrient alone may not warrant their availability for crop response until other interrelated factors have been considered. Even if the nutrients somewhat become available, their presence in the rhizosphere may not reach levels that can sustain increase alfalfa production.

Reports have shown that the relative levels of soil exchangeable K, calcium (Ca), and magnesium (Mg) can influence availability of P and K in the soil and the related crop response for adequate growth, due to their cationic characteristics [16] and the potential low solubility of dimagnesium phosphate ($MgHPO_4$) and dicalcium phosphate ($CaHPO_4$) [17]. Research findings on the relationship between cationic nutrients and their availability in the soil for plant uptake indicate that to determine the soil availability of cationic nutrient, the relative proportion of multiple nutrients ($K^+$, $Ca^{+2}$, $Mg^{+2}$, $Na^+$) ought to be considered rather than the levels of a single nutrient [18-20]. There is knowledge on the availability of K in relation to the soil exchangeable Ca and Mg levels [15, 21]. However, when in combination, the availability of P and K for crop response in reference to P and K relative to Ca and Mg levels in the soil is unknown.

Typically, when soil nutrient supply falls below critical levels, decreased yields occurs, hence yield response is often considered a better criterion to evaluate the interaction of nutrients such as P and K [22]. Nutrient interaction often takes place when the supply of one nutrient affects absorption and use of the other nutrient by the plant. Since K plays a more crucial role to induce interaction when in combination with other nutrients such as P [23,24], I hypothesized that P and K's availability for yield response of alfalfa is dependent on the relative levels of exchangeable Ca and Mg in the soil. The objective of the study was to evaluate alfalfa's response to P and K fertility relative to levels of Ca and Mg under field and greenhouse conditions.

## Materials and Methods

Field and greenhouse experiments were performed at the University of Wyoming James C. Hageman Sustainable Agriculture Research and Extension Center (SAREC), Lingle-WY (42° 15' 15" latitude N, 104° 20' 47" longitude W; elevation of 1272m), and at the University of Wyoming Laramie Research and Extension Center (LREC) greenhouse complex, Laramie-WY (41° 18' 40" latitude N, 104° 35' 37" longitude W elevation of 2,184m), respectively.

### Field Experiment

The experiment was conducted from September 2019 to October 2020 at a site that has a semiarid climate characterized with short growing season and an extensive winter period with 125days frost-free (above -4°C) period per year. Most of the precipitation is received in the months of May and July (Figure 1). Glyphosate (N-[phosphomethyl]-glycine) was applied onto the existing vegetation (forage sorghum [Sorghum bicolor (L.) Moench] stubbles) on the site, at a rate of 2.5kg ae $ha^{-1}$. The field was allowed to rest for 7 days prior to tillage operations (two times disking by using Krause 28' tandem disk [Kuhn Krause Inc., Hutchinson, KS-USA] followed by one time chain harrowing during the last week of August 2019) to ensure a weed free standard seed bed. Three cores of soil were sampled (0-15cm depth) from the experimental field and they were analyzed to determine the initial soil fertility status (Table 1), following standard soil testing procedures [25,26].

Treatments consisted of 10 selected combination rates of three P (0, 34, and 67kg $P_2O_5$ $ha^{-1}$), three K (0, 168, and 336kg $K_2O$ $ha^{-1}$), two Ca (0 and 560kg CaO $ha^{-1}$), and two Mg (0 and 56kg MgO $ha^{-1}$) organized in random complete blocks with three replications under a center-pivot-irrigation system. The combinations of P (triple superphosphate, TSP), K (muriate of potash), Ca (calcium oxide), and Mg (magnesium oxide) (Table 2) were broadcast to their designated plots at constant rate before planting. Fertilizer application was immediately followed by hand raking to incorporate fertilizer granules into the soil effectively. Pre-inoculated (alfalfa specific Rhizobium bacteria) seeds of Hi-Gest 360 (Alforex, https://www.alforexseeds.com/) were planted (September 3, 2019) on all plots at a seeding rate of 22 kg pure live seeds $ha^{-1}$, 1.2cm depth, and 18cm row spacing on 2.1m × 6 m size individual plots by using a 9-row tye drill (Model No. 104-4474, The Tye Company, Lockney, TX-USA). All plots were irrigated (~25 mm irrigation water) every 7 days (from June to September 2020) based on the available soil moisture. Manual weeding by hoeing of weeds was done during the seedling stage to reduce weed pressure.

Forage harvest was made in 2020. Two quadrats of alfalfa plants were sampled by mechanically harvesting the aboveground portion of the plants using a sickle and leaving a stubble of about 8-10cm. The remaining herbage were mowed and raked from the plots to mimic harvesting and baling. Harvested plant samples were oven-dried in a forced draft oven at 60°C for a minimum of 72hrs. Dry weight of the samples was measured and recorded as weight per unit quadrat area. This was used to estimate forage accumulation per hectare as dry matter (DM) basis.

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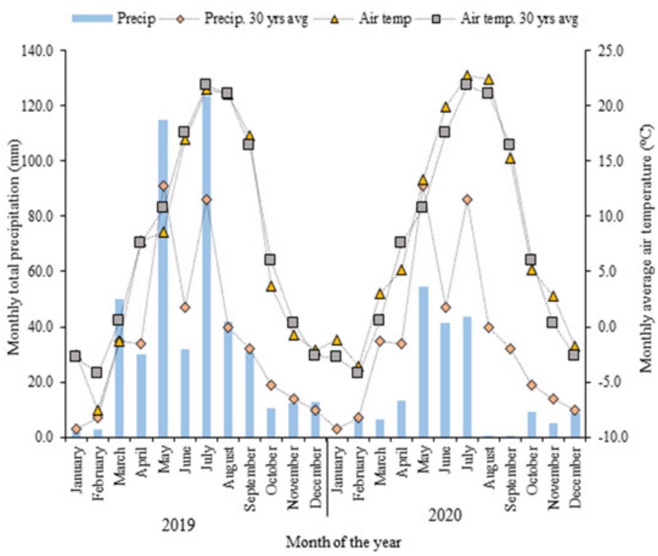


**Figure 1:** Monthly total precipitation (Precip.), and monthly average air temperature (Air Temp.), and 30-yrs. (1990–2020) average (avg) precipitation and air temperature during the study period at SAREC.

**Source:** Lingle field weather station (GHCND: USC00485612; https://www.ncdc.noaa.gov/cdo-web/).

### Greenhouse Experiment

The study was conducted under controlled conditions from October 2020 to March 2021 at the greenhouse complex of LREC. Daily average air temperature (21-27ºC) at the greenhouse was controlled both day and night (Figure 2) throughout the study period. Potting mix was prepared by sampling and mixing mortar sand and peat at a ratio of 2:1 (sand: peat) to ensure a uniform mixture. 2.0kg of the potting mixture was transferred into 1-gallon premium nursery plastic pots. The mixture was firmed (by using fist) to reduce air pockets and about 1.5 to 2cm watering space on the upper surface was allowed to prevent soil and fertilizer granules from falling during management practices. Each nursery pot measured 16.5cm upper diameter with a depth of 17.8cm, an actual liquid volume of 2744 $cm^3$, and perforated at the bottom for drainage outlets.

**Table 2:** Combinations of phosphorus, potassium, calcium, and magnesium used for the field study at SAREC in 2019 and the greenhouse study at LREC in 2020.

| | |
|---|---|
| **Field study** | |
| $T_1$: $P_0K_0$ | $T_6$: $P_0K_0Ca_{560}Mg_{56}$ |
| $T_2$: $P_{34}K_{168}$ | $T_7$: $P_{34}K_{168}Ca_{560}Mg_{56}$ |
| $T_3$: $P_{34}K_{336}$ | $T_8$: $P_{34}K_{336}Ca_{560}Mg_{56}$ |
| $T_4$: $P_{67}K_{168}$ | $T_9$: $P_{67}K_{168}Ca_{560}Mg_{56}$ |
| $T_5$: $P_{67}K_{336}$ | $T_{10}$: $P_{67}K_{336}Ca_{560}Mg_{56}$ |
| **Greenhouse study** | |
| $T_1$: $P_0K_0$ | $T_4$: $P_{67}K_{336}Ca_{4483}Mg_{897}$ |
| $T_2$: $P_{67}K_{336}$ | $T_5$: $P_{67}K_{336}Ca_{8967}Mg_{448}$ |
| $T_6$: $P_{67}K_{336}Ca_{8967}Mg_{897}$ | $T_6$: $P_{67}K_{336}Ca_{8967}Mg_{897}$ |

P source: Triple superphosphate (TSP, $Ca(H_2PO_4)_2$. $H_2O$); K source: Muriate of potash (KCl); Ca source: Calcium oxide (CaO); Mg source: Magnesium oxide (MgO)

The bottom of each pot was covered with paper towel to reduce soil loss through the drainage outlets especially during management practices such as watering. The potting mixture in each pot (60 pots in total) was deliberately leached by circulating adequate volumes of irrigation water (7 L; based on a series of pilot study) onto the soil in the pot. This was aimed at reducing the levels of exchangeable K, Ca, and Mg contained in the growth medium to establish a soil environment with low levels of exchangeable K, Ca, and Mg. The leached soils (in pots) were left to rest for 48 hrs followed by soil sampling for chemical analysis. The irrigation water was also sampled and analyzed (Table 3).

Chemical analysis of the soil and irrigation water was done following standard testing procedures at the Ward Laboratories, Inc., NE-USA (http://www.wardlab.com) to determine the K, Ca, Mg, and other important chemical properties. Treatments included 6 selected combination rates of two P (0 and 67kg $P_2O_5$ $ha^{-1}$), two K (0 and 336kg $K_2O$ $ha^{-1}$), three Ca (0, 4483, and 8967kg CaO $ha^{-1}$), and three Mg (0, 448, and 897kg MgO $ha^{-1}$), arranged in random complete blocks with 5 replications. The high rates of P and K used for the study were based on the best performing treatment of the field experiment.

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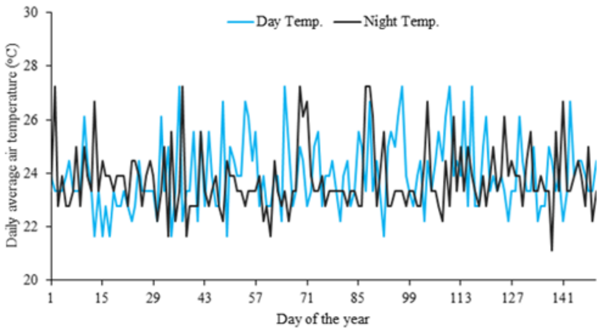


**Figure 2**: Daily average air temperature at LREC from October 2020 to March 2021.

**Table 3:** Test results of irrigation water used for the study at LREC in 2020.

| Water property | Test results |
|---|---|
| pH | 8.01 |
| Cations/Anions (me $L^{-1}$) | 4.3/4.2 |
| Electrical Conductivity (mmho $cm^{-1}$) | 0.40 |
| Total hardness, $CaCO_3$ (mg $kg^{-1}$) | 187 |
| Total alkalinity, $CaCO_3$ (mg $kg^{-1}$) | 164 |
| Total Dissolved Solids (mg $kg^{-1}$) | 237 |
| Carbonate (mg $kg^{-1}$) | < 1.00 |
| Bicarbonate (mg $kg^{-1}$) | 198 |
| Nitrate (mg $kg^{-1}$) | 1.06 |
| Potassium (mg $kg^{-1}$) | 1.13 |
| Calcium (mg $kg^{-1}$) | 50 |
| Magnesium (mg $kg^{-1}$) | 15 |
| Sodium (mg $kg^{-1}$) | 12 |
| Sodium Adsorption Ratio | 0.43 |
| Adjusted SAR | 0.54 |
| Sulfate (mg $kg^{-1}$) | 12 |
| Chloride (mg $kg^{-1}$) | 5.10 |
| Boron (mg $kg^{-1}$) | 0.01 |

### Planting, Fertilization, and Pot Management

Ten seeds of pre-inoculated (R. *meliloti*) seeds of Hi-Gest 360 alfalfa were hand seeded (October 26, 2020) in each pot containing the leached potting mix. Immediately after planting, each pot was placed in a round surface plastic bowl to collect soil water drained from the pots during irrigation. Following uniform emergence (3-7 days after planting), alfalfa seedlings in each pot were gradually thinned down to 5 plants by removing weak and unhealthy plants. The application rates of P, K, Ca, and Mg were estimated based on the initial soil test levels (Table 1). The amounts of P, K, Ca, and Mg required for each treatment were dissolved in an approximate volume of irrigation water and 15 ml of the solution (of each treatment) was dispensed onto the potting mix in the designated pot (November 16, 2020; one week after final thinning).

Other soil nutrients (sulfur and boron) were monitored for adequacy by checking for deficiency symptoms.

To keep the potting mix at field capacity, 100ml of irrigation water was applied to each pot (once a day) during the early stages of growth and regrowth. At the established phase of growth and when air temperatures were high (Figure 2), 200ml of irrigation water was applied to the pots (once a day). Prior to each irrigation, the drained soil water collected in the round surface plastic bowls under each pot were transferred into the respective pots to capture the leached nutrients.

### Data Collection, Harvesting and Processing

Data on plant growth, forage accumulation, and nutritive value were collected on alfalfa during each harvest period. A total of three forage harvests were made at a monthly interval from December 2020 to March 2021. At each harvest, the height of each of the 5 plants were taken by measuring from the base of the plant to the apex of the shoot using a ruler. Stem count of the plants was estimated by counting the number of plant stems in each pot. Upon harvesting, fresh weight of the harvested samples (all five plants) was measured and plant samples were oven-dried in a forced draft oven at 60°C for a minimum of 72hrs.

Dry weight of the samples was measured. This was used to estimate forage production per plant as forage DM accumulation of alfalfa. Plant samples used for DM determination were ground in a Wiley Mill (Model 4, Thomas Wiley, Laboratory Mill, Thomas Scientific, Swedesboro, NJ-USA) to pass through a 1-mm mesh. These were analyzed for forage nutritive value (crude protein; CP, neutral detergent fiber;


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NDF, acid detergent fiber; ADF, invitro dry matter digestibility; IVDMD, total digestible nutrient; TDN, and relative feed value; RFV) using Near-Infrared Reflectance Spectroscopy (NIRS, Foss DR6000 InfraXact analyzer, Silver Spring, MD-USA) that was calibrated from standard equations developed from a wet chemistry analysis of alfalfa samples chemically assayed for forage nutritive value components.

Prior to scanning of the samples for forage nutritive value, a check sample was scanned to examine the accuracy and ensure that the NIRS calibration is intact. The roots of each plant were removed from the potting mix after the final harvest. These were washed thoroughly and oven-dried in a forced draft oven at 60ºC for a minimum of 48 hrs. Dry weight of the samples was measured to estimate for root DM of alfalfa per plant basis.

### Statistical Analyses

Analysis of variance procedure was performed separately for each study on plant growth, forage DM accumulation, and nutritive value data by using the mixed effect procedure (PROC MIXED), and the MEANS option in Statistical Analysis System [27]. Treatments and harvest frequency were considered fixed effects, and replicates as random effects in the model. Validity of equal variance, normality, and independent assumptions on the error terms were confirmed by assessing the residuals as described by Montgomery [28]. For each response variable, main effect and interaction effect of the treatments were tested against their respective error term and significance was declared at $\alpha = 0.05$. Post-hoc mean separations were conducted by using Fisher's protected least significance difference.

## Results and Discussion

### Field Study

Forage accumulation: The initial soil test result revealed that the soil had an alkaline pH and the exchangeable soil K, Ca, and Mg levels were in high ranges (Table 1). This is typical of soils in Wyoming and surrounding states due to the higher amount of potential evaporation than average annual precipitation the region receives. Alfalfa has high nutrient demand, particularly K, and therefore nutrient build-up in an alfalfa stand is equally important as the downscaling of interrelated factors critical to the nutrient's availability to be taken-up by plants for adequate growth. Naturally, alkaline soils are rich in nutrients because the rocks and sediments weathers over time which releases nutrients including P, K, Ca, Mg, sulfur and micronutrients in the soil [29]. However, when the soil pH approaches 8.0 or higher, availability of some nutrients is constrained, and management strategies might be beneficial to unlock these nutrients to become plant available.

A balanced nutrition of P and K has been shown to have a positive impact on the forage accumulation and persistence of alfalfa [7,9]. Likewise, findings of the present study showed a significant high yield response when alfalfa was fertilized with P×K (Table 4), which indicates that the initial levels of P and K (control plots) were not adequate to meet alfalfa's nutritional needs for an increased forage accumulation. This is attributable to a slow release of the nutrients from the soil due to a possible constraint of P and K by other interrelated factors (such as the relative levels of soil Ca and Mg) which made the nutrients unavailable for plant uptake that leads to yield response. Compared to the unfertilized alfalfa, the general higher yield response of alfalfa fertilized with P×K shows that the increased levels of P×K promoted the availability of the nutrients for plant uptake which led to higher yield response.

Total forage accumulation of alfalfa was highest (13.8 Mg $ha^{-1}$, ~ 44% yield increase over the control) when alfalfa was fertilized with high rates of P and K combination ($P_{67}K_{336}$). Applying $P_{67}K_{336}$ with $Ca_{560}Mg_{56}$ to alfalfa was consistent in producing greatest total forage accumulation (14.5 Mg $ha^{-1}$; ~51% yield increase over the control) (Table 4). Depending on their relative levels, cationic nutrients such as $Ca^{+2}$ and $Mg^{+2}$ are critical to the availability of P and K in the soil for plant uptake [16,30].

The roles of P and K are interdependent and therefore, a blend of both nutrients interacted to form strong bonds that can interact with other nutrients to affect their relative concentrations in the soil [7,31]. As observed from the results of this study, the high P and K levels interacted, and the interaction effect maintained a positive balance of P and K which and potentially stimulated the concentrations of P and K to dominate the exchange sites and soil space at the expense of Ca and Mg levels in the soil. Hence the availability and uptake of P and K by alfalfa for yield response. This explains the higher yield response of alfalfa fertilized with $P_{67}K_{336}$ even in a soil with elevated levels of exchangeable Ca and Mg. High rates of P × K was adequate to produce a well-balanced nutrition to supply the needed quantities of P and K to reach the nutrient sufficiency range and produce an optimized effect for an improved physiology, growth and development of alfalfa.

### Greenhouse Study

Findings of the field study showed that fertilizing alfalfa with increased rates of P×K results in high yield response. This was true for P×K with $Ca_{560}Mg_{56}$ and without $Ca_{560}Mg_{56}$ associations. However, the rates of Ca and Mg used for the study were confined to 560kg $ha^{-1}$ $yr^{-1}$ and 56kg $ha^{-1}yr^{-1}$, respectively, which provided limited information on the range of Ca and Mg levels relative to $P_{67}K_{336}$ needed to produce yield response. The greenhouse study therefore, aimed to supplement the findings of field study with the range of Ca and Mg levels relative to $P_{67}K_{336}$ needed to produce yield response of alfalfa.

Plant growth, forage accumulation and root biomass: Treatment affected ($P<0.05$) alfalfa's growth and yield. The application of P×K to alfalfa resulted in higher plant height compared to the general low heights of alfalfa fertilized with P×K with Ca and Mg association. The lowest plant height (4cm) was produced by the unfertilized alfalfa (Table 5). Similar trend of results was observed for alfalfa's vigor such that $P_{67}K_{336}$-fertilized alfalfa had high vigor [22] whiles unfertilized alfalfa gave low vigor [12]. Compared to $P_{67}K_{336}$, vigor of alfalfa that received $P_{67}K_{336}$ with Ca and Mg associations was generally low and it declined steadily with as soil Ca and Mg concentrations increased (Table 5). These results reflected in alfalfa's stem number such that unfertilized alfalfa produced the least [32] stem count whiles the highest stem count [5] was produced by $P_{67}K_{336}$-fertilized alfalfa. Stem count generally reduced when alfalfa was fertilized with $P_{67}K_{336}$ on a soil with high Ca and Mg levels, and the reduction continued as the levels of soil Ca and Mg increased compared to stem count of $P_{67}K_{336}$-fertilized alfalfa (Table 5).

Moreover, forage accumulation was highest for alfalfa fertilized with $P_{67}K_{336}$ (1309 mg $plant^{-1}$) followed by alfalfa fertilized with $P_{67}K_{336}$ on a soil with low levels of Ca and Mg (1046 mg $plant^{-1}$). It was evident that alfalfa's yielding potential continually reduced when it received $P_{67}K_{336}$ on a soil with increased concentrations of Ca and Mg (Table 5). Similar findings were observed for root biomass such that the greatest (6260mg $plant^{-1}$) root DM was produced at $P_{67}K_{336}$ and it started to decline when $P_{67}K_{336}$ was applied to alfalfa on a soil with elevated levels of Ca and Mg (Table 5). The general higher yield response for fertilized alfalfa compared to unfertilized alfalfa is associated to beneficial effects of fertilization in alfalfa forage systems as shown in earlier studies [3,8,32,33]. Applying P×K to alfalfa promoted its growth such that plant height, vigor, stem count, forage accumulation, and root DM were significantly improved. The improvement is linked to enhanced availability and uptake of P and K for optimum plant nutrition which stimulated growth. Thus, the high rates of P and K interacted to produce a well-balanced nutrition which fostered the availability of nutrients in the soil for adequate uptake by alfalfa to produce higher yield responses.

As shown in Table 5, alfalfa's growth and forage accumulation often reduced when it was fertilized with $P_{67}K_{336}$ in combinations with Ca and Mg rates. This demonstrates the potential inhibiting effect of Ca and Mg levels on the availability of P and K for plant uptake to produce yield response [15,16]. Thus, the presence of elevated levels of Ca and Mg levels restricted the availability of adequate levels of P and K levels in the soil solution to be accessible by alfalfa to improve its physiological plant processes for increased growth and development, hence the reduced yield response. The general decreasing trend observed in plant height, vigor, stem count, forage accumulation, and root DM of alfalfa as Ca and Mg proportions increased relative to $P_{67}K_{336}$ provides evidence to suggest that low concentrations of soil Ca and Mg relative to $P_{67}K_{336}$ was required to produce high yield response of alfalfa. Finding of the study agreed with findings of previous studies which showed that forage yield production is determined by yield components [34-36].

**Table 5:** Effect of phosphorus and potassium relative to calcium and magnesium levels on plant growth, forage accumulation (dry matter [DM] yield), and root DM of alfalfa (Hi-Gest 360) under controlled conditions at LREC from October 2020 to March 2021.

| Treatment (kg ha$^{-1}$) | Plant height | Plant vigor | Stem count | DM yield | Root DM |
|---|---|---|---|---|---|
| | (cm) | | m$^{-2}$ | mg plant$^{-1}$ | |
| $P_0K_0$ | 4 c† | 3 c | 5 c | 317 d | 1060 d |
| $P_{67}K_{336}$ | 13 a | 8a | 14 a | 1309 a | 6260 a |
| $P_{67}K_{336}Ca_{4483}Mg_{448}$ | 11 ab | 6 b | 8 b | 1046 b | 3771 b |
| $P_{67}K_{336}Ca_{4483}Mg_{897}$ | 10 b | 5 b | 6 bc | 884 c | 3054 c |
| $P_{67}K_{336}Ca_{8967}Mg_{448}$ | 10 b | 5 b | 6 bc | 779 c | 2727 c |
| $P_{67}K_{336}Ca_{8967}Mg_{897}$ | 11 ab | 5 b | 6 bc | 755 c | 2929 c |
| Average | 9 | 5 | 8 | 848 | 3300 |

Plant vigor was rated on a scale of 1 to 10, 1: lowest vigor and 10: highest vigor.

† Within each column, means followed by same lower-case letter are not significantly different at 0.05 probability level.

Nutritive value: Forage nutritive value of alfalfa differed ($P < 0.05$) among the treatments for CP, NDF, and IVDMD but not for ADF, TDN, and RFV (Table 6). Alfalfa's CP (267g kg$^{-1}$) and IVDMD (807g kg$^{-1}$) increased when it was fertilized with $P_{67}K_{336}$. Notably, similar trend of CP (263g kg$^{-1}$) and IVDMD (790g kg$^{-1}$) concentrations were produced by alfalfa that received $P_{67}K_{336}Ca_{4483}Mg_{448}$ (Table 6). The unfertilized alfalfa produced the lowest CP and IVDMD concentrations (CP, 214g kg$^{-1}$; IVDMD, 738g kg$^{-1}$). Concentrations of NDF in alfalfa was higher for $P_{67}K_{336}$-fertilized alfalfa than NDF levels of alfalfa fertilized with $P_{67}K_{336}$ on a soil with increasing levels of Ca and Mg. Alfalfa's ADF, TDN, and RFV concentrations were similar and comparable for all treatments (Table 6). The treatment effect on CP, NDF, and IVDMD confirms the influential role of P and K on nutritive value of alfalfa as reported by previous studies [7,11]. This is attributable to the reduced levels of the initial soil P and K, which potentially allowed for response to applied P and K.

**Table 6:** Effect of phosphorus and potassium in association with calcium and magnesium, and harvest time on forage nutritive value of alfalfa (Hi-Gest 360) under controlled environments at LREC from October 2020 to March 2021.

| Treatment(kg ha$^{-1)}$ | CP | NDF | ADF | IVDMD | TDN | RFV |
|---|---|---|---|---|---|---|
| | g kg$^{-1}$ | | | | | |
| $P_0K_0$ | 214 c† | 295 ab | 219 a | 738 cd | 778 a | 227 a |
| $P_{67}K_{336}$ | 267 a | 306 a | 200 a | 807 a | 800 a | 223 a |
| $P_{67}K_{336}Ca_{4483}Mg_{448}$ | 263 a | 291 b | 197 a | 790 ab | 803 a | 236 a |
| P67$K_{336}Ca_{4483}Mg_{897}$ | 248 a | 289 b | 205 a | 761 bcd | 795 a | 235 a |
| $P_{67}K_{336}Ca_{8967}Mg_{448}$ | 220 bc | 291 b | 216 a | 736 d | 783 a | 231 a |
| $P_{67}K_{336}Ca_{8967}Mg_{897}$ | 245 ab | 299 ab | 198 a | 770 bc | 802 a | 228 a |
| Average | 243 | 295 | 206 | 767 | 794 | 230 |

CP: crude protein, NDF: neutral detergent fiber, ADF: acid detergent fiber, IVDMD: in-vitro dry matter digestibility, TDN: total digestible nutrients, RFV: relative feed value.

† Within each column, means followed by same lower-case letter are not significantly different at 0.05 probability level.

The high nutritive value of alfalfa fertilized with $P_{67}K_{336}Ca_{4483}Mg_{448}$ is associated to the low plant growth produced by $P_{67}K_{336}Ca_{4483}Mg_{448}$ compared to $P_{67}K_{336}$ (Table 4). This is associated with alfalfa's yield response to P and K levels and the likelihood of altering the plant's morphology and physiology in ways that increases the leaf number relative to the stem tissues [7]. Compared to $P_{67}K_{336}Ca_{4483}Mg_{448}$, similar trend of forage nutritive value was produced by $P_{67}K_{336}$-fertilized alfalfa except for the high NDF levels (which is due to high plant growth). Except for NDF, there was a general declining trend of the forage nutritive value of alfalfa fertilized with $P_{67}K_{336}$ in a soil with Ca and Mg concentrations exceeding $Ca_{4483}Mg_{448}$. This is associated with the inhibiting effect of Ca and Mg levels on P and K's availability and uptake for improved plant production.

## Summary and Conclusions

Fertilizing alfalfa with $P_{67}K_{336}$ produced the highest yield response of alfalfa under field and greenhouse environments. Alfalfa's forage production potential increased when it received P and K in soils with low to moderate levels of exchangeable Ca and Mg. The levels of soil exchangeable Ca and Mg relative to levels of P and K have shown enormous potential to constraint the P and K to be unavailable for plant uptake to produce yield response. It was evident from the greenhouse study that alfalfa's response to applied P×K decreases on soils with elevated levels of Ca and Mg rates beyond $Ca_{4483}Mg_{448}$. The finding supported results of the field study which suggested that applying high rates of P and K to alfalfa on soil with low levels of Ca and Mg has the potential to induce significant yield response in alfalfa. Growers and stakeholders of alfalfa should therefore consider the soil exchangeable levels of Ca and Mg on alfalfa fields to facilitate decisions on the proper rates of P and K in their nutrient management program for an improved and sustainable alfalfa.

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## Conflict of Interest

Th author declare no conflict of interest.

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