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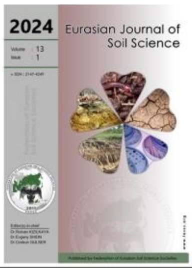

Impact of phosphorus fertilization on the yield and quality of various Alfalfa (*Medicago sativa* L.) varieties in light chestnut soils

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Abstract

This study investigates the impact of phosphorus fertilization on the yield and quality of various alfalfa (*Medicago sativa* L.) varieties grown in light chestnut soils. Conducted over a three-year period from 2013 to 2015, the research was carried out in the Karasay district of the Almaty region under irrigated conditions. The experiment included six alfalfa varieties: NS Alfa, VS Banat, Mediana, Nera, Niagara, and Kokoray. Four phosphorus treatments were applied: control (no phosphorus), 60 kg/ha (P60), 90 kg/ha (P90), and 120 kg/ha (P120), using double superphosphate as the phosphorus source. The results demonstrated that phosphorus fertilization significantly enhanced both the yield and quality of alfalfa. Across all varieties, the highest yield was observed with the application of 120 kg/ha phosphorus. For instance, NS Alfa's yield increased from 283.3 c/ha in the control to 349.7 c/ha with P120, reflecting a 23% increase. Similarly, VS Banat and Mediana exhibited yield increases of 23% and 25%, respectively, at the highest phosphorus level. The study also revealed improvements in the nutritional quality of alfalfa hay. Crude protein content increased from 20.3% to 22.0% in NS Alfa, while digestible protein content rose from 11.20% to 12.40%. Other quality parameters, including fat and carotene content, also improved significantly with higher phosphorus levels. Moreover, the availability of nitrate nitrogen and mobile phosphorus in the soil increased progressively with higher phosphorus application rates, contributing to better nutrient uptake and overall plant health. This research underscores the importance of phosphorus fertilization in maximizing alfalfa yield and quality. The findings suggest that the optimal phosphorus application rate for enhancing alfalfa production in light chestnut soils is 120 kg/ha, providing valuable insights for sustainable agricultural practices in similar agro-ecological zones.

Keywords: Phosphorus fertilization, Alfalfa yield, Alfalfa quality, Light chestnut soils, Sustainable agriculture.

Introduction

Phosphorus is one of the essential macronutrients required for plant growth and development. It is a key component of ATP, nucleic acids, and phospholipids, all of which are vital for energy transfer, genetic information storage, and membrane integrity in plants (Marschner, 1995; Khan et al., 2023). Phosphorus deficiency can severely limit plant growth, leading to reduced biomass production and poor crop quality. This

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is particularly significant in leguminous crops like alfalfa, which have high phosphorus requirements to support their vigorous growth and nitrogen-fixing capabilities (Meng et al., 2021).

Alfalfa (*Medicago sativa* L.), known as the 'Queen of Forages', is one of the oldest wild plants, originally found in the mountainous forests of the Mediterranean region in Southwest Asia. The name 'alfalfa' is derived from the Arabic word 'Al-Fasfasa', which means 'father of all plants' (Suwignyo et al., 2022). Alfalfa is a highly valued forage crop known for its high nutritional content and adaptability to various environmental conditions. It is widely cultivated for its high protein content and digestibility, making it an essential component of livestock diets. The demand for high-quality alfalfa hay has increased, emphasizing the need for improved cultivation practices to enhance both yield and nutritional value (Capstaff and Miller, 2018). The importance of alfalfa in sustainable agriculture cannot be overstated, as it plays a crucial role in improving soil structure, enhancing soil fertility, and providing high-quality forage for animals (Xu et al., 2024). Previous studies (Berg et al., 2005; Macolino et al., 2013; Liu et al., 2013; Madani et al., 2014; Al-Kahtani et al., 2017; Li and Liu, 2024) have shown that phosphorus fertilization can significantly improve the growth and productivity of alfalfa by enhancing root development and increasing the availability of essential nutrients in the soil. Studies have shown that phosphorus application enhances root development, increases nutrient uptake, and improves overall plant health, leading to higher yields and better quality forage. For instance, Yıldız and Türk (2015) reported that phosphorus fertilization significantly increased biomass production in forage crops, while Marschner (1995) and Havlin et al. (2005) emphasized the importance of phosphorus in improving soil fertility and crop productivity.

Light chestnut soils, which are prevalent in many agricultural regions, often exhibit low phosphorus availability due to their high calcium carbonate content and alkaline pH (Saparov, 2014). This characteristic makes these soils less suitable for high-yielding crops without appropriate fertilization strategies (Maxotova et al., 2021; Zhaksybayeva et al., 2022; İslamzade et al., 2023). To address this challenge, it is crucial to determine the optimal phosphorus application rates that can maximize alfalfa yield and quality while maintaining soil health.

Despite the well-documented benefits of phosphorus fertilization, there is limited research specifically addressing its impact on the yield and quality of different alfalfa varieties grown in light chestnut soils. This study aims to fill this gap by evaluating the effects of various phosphorus application rates on the growth, yield, and nutritional quality of several alfalfa varieties under irrigated conditions in the Almaty region. The findings will provide valuable insights for optimizing fertilization strategies to maximize alfalfa productivity and quality in similar agro-ecological zones. The objective of this study is to assess the impact of different levels of phosphorus fertilization on the yield and quality of various alfalfa varieties grown in light chestnut soils, thereby identifying the optimal phosphorus application rate for enhancing alfalfa production in these conditions.

Material and Methods

Experimental site

The research was conducted from 2013 to 2015 in irrigated light chestnut soils at the Kazakh Research Institute of Agriculture and Plant Growing located in the Karasay district of the Almaty region, Kazakhstan (Figure 1).

Figure 1. Experimental area

The soil of the experimental area belongs to the general soil type of light chestnut. Before conducting the experiment, the soil sample was analyzed by the Kazakh National Agrarian Research University. Some characteristics of the experimental field's soil are presented in Table 1.

Table 1. Some characteristics of the experimental field's soil

Depth (cm)	Organic matter (%)	Total Nitrogen (%)	Mobile Nitrogen (mg/kg)	Mobile Phosphorus (mg/kg)	Mobile Potassium (mg/kg)	Bulk Density (g/cm^3)
0-20	2.45	0.193	73.8	25.0	460	1.20
20-40	2.30	0.156	71.9	20.1	430	1.25

Climatic data

The experimental area has a continental climate with hot summers and cold winters, and low precipitation. Despite occasional high rainfall, irrigation is essential for high forage crop yields. The region experiences an average of 219 days per year with temperatures above +5ºC. In the Almaty region, the transition from negative to positive average daily temperatures occurs between March 5 and 10. January, the coldest month, has average temperatures between -1.9ºC and -7.6ºC, while July, the hottest month, ranges from +27.8ºC to +31.4ºC. The frost-free period lasts 5-6 months. Annual precipitation averages 332-645 mm, with the most rainfall from March to June. In arid years, rainfall can be 1.5-2.0 times below average, while in wet years, it can exceed the norm by the same ratio. Snow cover lasts 1.5 to 3.0 months, with depths not exceeding 15-20 cm. The monthly temperature and precipitation averages for the Karasay District, where the experimental field is located, are presented in Figure 2.

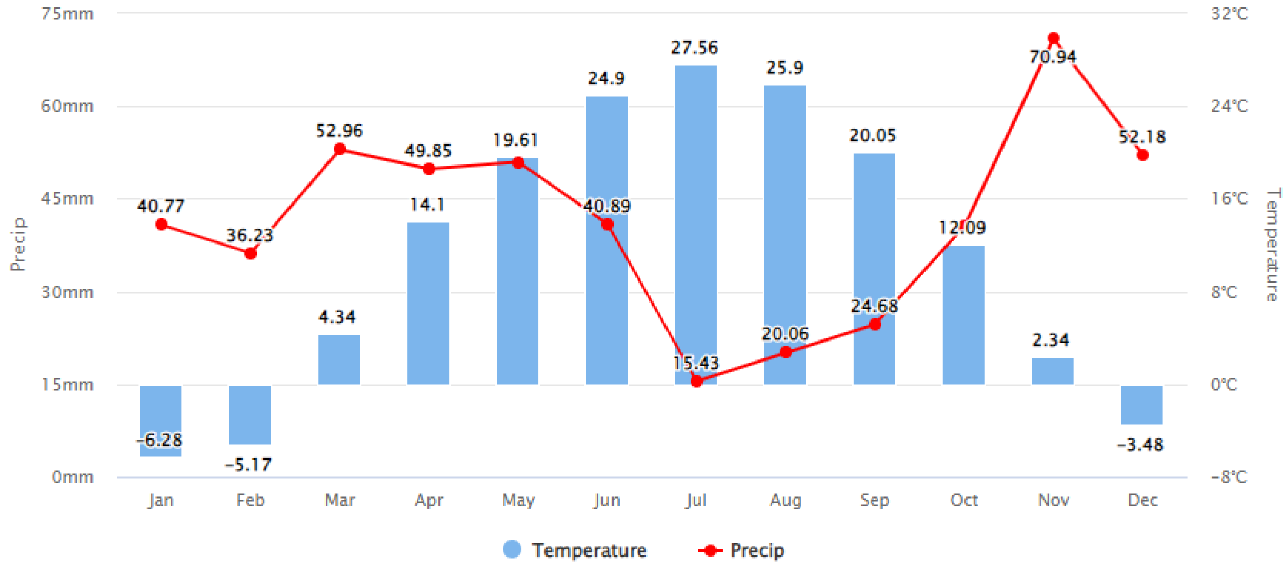

Figure 2. Temperature and precipitation averages in the Karasay District (in Almaty Region, Kazakhstan) where the experimental field is located

Alfalfa (Medicago sativa L.) varieties

Six alfalfa varieties were used in the experiment, including the local Kazakh variety, Kokoray, and five Serbian varieties: NS Alfa, VS Banat, Mediana, Nera, and Niagara. VS Banat is an early variety with rapid growth and good drought and cold tolerance, yielding 85-100 t/ha of green mass and 18-20 t/ha of hay, with 20.1% protein content. NS Alfa, a synthetic variety, thrives in fertile soils, is cold-resistant, and supports frequent mowing, producing over 80 t/ha of green mass and 20 t/ha of hay, with 20-22% protein content. Niagara is disease-resistant, drought-tolerant, and performs well on degraded soils, yielding over 80 t/ha of green mass and 20 t/ha of hay, with 22% protein content. Nera, an early variety with a deep root system, is drought-resistant and regenerates quickly, yielding over 80 t/ha of green mass and 20 t/ha of hay, with 20.7% protein content. NS Mediana, developed through hybridization, grows well in various conditions, is drought and cold-resistant, and yields about 20 t/ha of hay, with an average protein content of 21%.

Experimental Design

The alfalfa was sown using specialized equipment with a row spacing of 15 cm, and a seeding rate of 16 kg per hectare. The experimental design was a randomized complete block design, with each treatment repeated three times. Each plot measured 15 meters in length and 1 meter in width, resulting in a total plot area of 15 m^2 for each alfalfa variety. Double superphosphate (42% P_2O_5) was used as the phosphorus source for all treatments.

The experiment included four phosphorus fertilizer treatments:

- Control: No phosphorus fertilizer applied.
- P60: 60 kg/ha of phosphorus applied.
- P90: 90 kg/ha of phosphorus applied.
- P120: 120 kg/ha of phosphorus applied.

Soil and Plant Analysis Methods

During the trial period, nitrate nitrogen in soil samples taken from each plot at the stages of the 1st cutting, 2nd cutting, 3rd cutting, and 4th cutting of alfalfa varieties was determined using the Kjeldahl distillation method in 1N KCl extract, and mobile phosphorus was determined according to the Machigin method (Jones, 2001). At the end of the trial, yield and yield components (Crude Protein, N-free Extractives, Cellulose, Ca, Ash, Carotene, Fat, Digestible protein) in alfalfa variety samples taken from all plots were determined as reported by Galyean (2010).

Results and Discussion

Yield of Alfalfa

The application of phosphorus fertilizers significantly increased the yield of alfalfa across all varieties studied from 2013 to 2015. The different levels of phosphorus application (60, 90, and 120 kg/ha) showed a marked improvement in yield compared to the control (Table 2).

Table 2. Yield of Alfalfa varieties depending on the use of phosphorus fertilizer (2013-2015)

Variety	Treatment	2013 Yield (t/ha)	2014 Yield (t/ha)	2015 Yield (t/ha)	Total Yield (c/ha)	Additional Yield (c/ha)	Increase (%)
NS Alfa	Control	27.1	129.2	127.0	283.3	-	-
	P60	30.1	145.4	138.8	314.3	31.0	11
	P90	30.7	148.5	141.4	320.6	37.3	13
	P120	43.0	155.9	150.8	349.7	66.4	23
VS Banat	Control	28.0	130.9	124.5	283.4	-	-
	P60	28.8	147.9	143.9	320.6	37.2	13
	P90	29.8	151.2	148.0	329.0	45.6	16
	P120	32.4	161.0	155.4	348.8	65.4	23
Mediana	Control	25.1	126.4	122.9	274.4	-	-
	P60	33.2	134.3	134.3	301.8	27.4	10
	P90	30.7	144.7	137.8	313.2	38.8	14
	P120	37.0	153.2	153.2	343.4	69.0	25
Nera	Control	23.2	115.5	107.1	245.8	-	-
	P60	29.0	127.1	120.3	276.4	30.6	12
	P90	28.0	135.2	126.2	289.6	43.8	18
	P120	33.2	148.6	148.6	330.4	84.6	34
Niagara	Control	19.8	122.6	111.7	254.1	-	-
	P60	26.1	132.4	122.2	280.7	26.6	10
	P90	28.4	139.1	131.1	298.6	44.5	18
	P120	41.0	145.3	141.1	327.4	73.3	29
Kokoray	Control	27.1	123.5	113.4	264.0	-	-
	P60	30.1	144.9	145.0	320.0	56.0	21
	P90	30.7	151.0	142.2	323.9	59.9	22
	P120	35.0	155.9	150.0	340.9	76.9	29

In 2013, the initial yields were relatively lower across all varieties and treatments, possibly due to the initial establishment periods of the alfalfa. However, as phosphorus application rates increased, yields showed noticeable improvement. For example, NS Alfa exhibited a marked increase from 27.1 t/ha in the control to 43.0 t/ha with 120 kg/ha phosphorus in 2013. This trend continued in subsequent years, with the highest increases observed in 2015, where NS Alfa achieved a yield of 349.7 c/ha, representing a 23% increase over the control.

VS Banat and Mediana also showed considerable yield improvements. VS Banat's yield increased from 28.0 t/ha in the control to 32.4 t/ha with 120 kg/ha phosphorus in 2013. By 2015, this variety achieved a total yield of 348.8 c/ha, reflecting a 23% increase. Mediana's yield improved from 25.1 t/ha in the control to 37.0 t/ha with 120 kg/ha phosphorus in 2013, with a total yield of 343.4 c/ha by 2015, representing a 25% increase.

Kokoray exhibited the highest yield increase of 21% with 60 kg/ha phosphorus in 2013. By 2015, with 120 kg/ha phosphorus, Kokoray's yield reached 340.9 c/ha, representing a 29% increase. This substantial increase underscores the effectiveness of phosphorus in enhancing the productivity of this variety.

The application of 90 kg/ha phosphorus resulted in significant yield increases for all varieties. NS Alfa's yield increased by 13%, VS Banat by 16%, and Mediana by 14%. These results are consistent with findings from similar studies that highlight the critical role of phosphorus in improving crop yield by enhancing nutrient uptake and utilization efficiency (Havlin et al., 2005; Yıldız and Türk, 2015). The highest efficiency was observed with the application of 120 kg/ha phosphorus. This level of application resulted in the most significant yield increases across all varieties, with NS Alfa, VS Banat, and Mediana achieving yields of 349.7 c/ha, 348.8 c/ha, and 343.4 c/ha, respectively. Nera and Niagara also showed notable yield increases, with Nera's yield increasing by 34% and Niagara by 29%. These results highlight the optimal rate of phosphorus application necessary to maximize alfalfa yield, corroborating studies that advocate for balanced fertilization strategies to achieve sustainable high yields (Berg et al.; 2005; Madani et al., 2014; Al-Kahtani et al., 2017; Maxotova et al., 2021; Alimkhanov et al., 2021; Kamzina et al., 2022; Muminova et al., 2022).

These findings emphasize the importance of phosphorus fertilization in maximizing the yield of alfalfa varieties. The application of 120 kg/ha phosphorus was identified as the most effective rate for achieving the highest yield improvements across all studied varieties. This rate not only enhanced yield but also improved the overall quality of the alfalfa, making it a critical component of alfalfa cultivation practices in light chestnut soils. Phosphorus fertilizer is a key factor affecting seed yield and has a significant impact on the dynamic changes in plant stems, inflorescence number, dry matter accumulation, and seed yield (Liu et al., 2020; Loeppky et al., 1999). Liu et al. (2013) reported that under alkaline soil conditions in arid areas, a phosphorus fertilizer dosage of 150 kg/ha can promote an increase in alfalfa seed yield when the soil phosphorus content reaches a moderate level. Buglass (1964) indicated that there was no significant role for phosphorus in increasing forage seed production in southern Saskatchewan, reflecting the variability of soil phosphorus status and the influence of annual weather effects. In this experiment, when phosphorus fertilizer was applied at 120 kg/ha, the yield increased by 25% and 34% compared to the control, respectively, in each year. This indicates that phosphorus fertilizer can increase the seed yield of alfalfa, but the effect is related to the selected alfalfa varieties, climatic conditions, soil conditions, and phosphorus fertilizer application (Al-Kahtani et al., 2017; Liu et al., 2013).

Quality of Alfalfa

The quality of alfalfa, as measured by its nutritional content, improved significantly with the application of phosphorus fertilizers. The study examined various parameters such as crude protein (CP), digestible protein (DP), non-nitrogenous extractives (NNE), fat content, and carotene content across different varieties of alfalfa (Table 3).

The application of phosphorus fertilizer had a notable impact on the crude and digestible protein content in all alfalfa varieties. NS Alfa showed an increase in crude protein from 20.3% in the control to 22.0% with 120 kg/ha phosphorus, and digestible protein increased from 11.20% to 12.40%. Similarly, VS Banat's crude protein content increased from 21.8% to 24.0%, and digestible protein from 10.0% to 11.35%. Mediana's crude protein rose from 22.3% to 24.5%, and digestible protein from 11.80% to 14.0%. An increase in crude and digestible protein content led to a decrease in non-nitrogenous extractives content. For instance, phosphorus fertilizer reduced non-nitrogenous extractives from 35.8% to 24.7% in NS Alfa, and similar reductions were observed in other varieties. This aligns with the findings of Sumner and Farina (1986) and Xu et al. (2024), who noted that phosphorus application can enhance protein content while reducing non-nitrogenous extractives in forage crops.

Phosphorus fertilizer also positively affected the fat and carotene content of alfalfa hay. The application of 120 kg/ha phosphorus increased the fat content in NS Alfa to 2.8%, compared to 2.0% in the control. Similar increases were observed in other varieties, such as VS Banat and Niagara, where fat content rose to 2.8% and 2.6%, respectively. The carotene content also showed significant improvement with phosphorus application. For example, NS Alfa's carotene content increased from 33.6% in the control to 36.7% with 120 kg/ha phosphorus. This trend was consistent across other varieties, with notable increases in VS Banat, Mediana, and Nera. There are genetic variations in yield and its components among and within populations of alfalfa (Campbell and He, 1997) and the response of yield components to plant genetics and management techniques is also different (El-Hifny et al.,2019; Sengul, 2006). Yield and its components exhibit genetic variability both among and within alfalfa populations (Campbell and He, 1997). Additionally, the response of these yield components to plant genetics and various management techniques varies significantly (El-Hifny et al., 2019; Sengul, 2006). This nuanced understanding is crucial for tailoring effective agricultural practices, particularly in projects focused on enhancing crop yield and quality.

Table 3. Effect of Phosphorus Fertilizer on the Composition of Alfalfa Hay

Variety	Treatment	Crude Protein (%)	N-free Extractives (%)	Cellulose (%)	Ca (%)	Ash (%)	Carotene (%)	Fat (%)	Digestible Protein (%)
NS Alfa	Control	20.0	30.2	40.0	2.17	9.6	33.6	2.0	11.08
	P60	20.3	30.0	42.0	2.05	10.8	34.8	2.3	11.20
	P90	21.5	29.8	41.8	1.98	11.5	36.0	2.7	11.38
	P120	22.0	30.0	42.8	1.92	12.8	36.7	2.8	12.40
VS Banat	Control	20.1	35.2	30.1	2.80	13.0	40.0	1.8	9.00
	P60	21.8	34.0	32.0	2.77	13.8	41.2	2.0	10.00
	P90	22.4	34.0	32.6	2.61	14.6	43.0	2.1	11.00
	P120	24.0	33.3	34.0	2.52	16.0	43.9	2.3	11.35
Mediana	Control	21.4	28.0	38.0	2.45	11.5	38.0	2.4	9.50
	P60	22.3	27.7	38.2	2.15	12.8	39.0	2.6	11.80
	P90	23.2	25.0	39.0	1.90	13.3	40.5	2.9	12.44
	P120	24.5	25.1	40.8	1.87	15.8	41.0	2.8	14.00
Nera	Control	20.7	36.8	29.4	2.30	9.6	40.0	1.6	10.00
	P60	21.8	35.7	31.3	2.22	11.2	41.0	1.7	11.20
	P90	22.5	35.8	30.6	2.24	12.4	41.6	1.9	12.60
	P120	23.0	35.1	32.0	2.21	14.4	42.3	1.8	14.80
Niagara	Control	22.0	27.5	33.5	2.18	10.0	38.2	2.2	10.80
	P60	23.0	26.0	35.0	2.14	11.5	39.0	2.3	12.70
	P90	24.5	26.3	37.7	2.06	14.0	40.5	2.5	13.80
	P120	26.0	25.5	39.0	2.00	16.0	41.0	2.6	14.50
Kokoray	Control	15.6	26.0	37.0	2.20	9.9	35.0	1.9	9.06
	P60	17.2	25.0	38.0	2.21	12.0	37.0	2.1	11.00
	P90	17.0	24.8	38.3	2.15	13.2	36.0	2.4	12.51
	P120	17.6	24.7	39.0	2.10	14.6	38.0	2.6	12.90

These results highlight the importance of phosphorus fertilization in enhancing the nutritional quality of alfalfa. The improvements in crude and digestible protein, fat, and carotene contents indicate that phosphorus not only boosts yield but also enriches the nutritional profile of the crop. Such enhancements are crucial for improving the overall feed value of alfalfa, making it more beneficial for livestock. The application of 120 kg/ha phosphorus was particularly effective across all varieties studied, indicating its critical role in improving the nutritional value of alfalfa hay. The findings are supported by previous research, including studies by Wang et al (2008) and Macolino et al. (2015), which emphasize the role of phosphorus in improving forage quality by enhancing nutrient uptake and utilization efficiency.

Nutrient Availability

The nutrient availability in the soil was significantly influenced by the application of phosphorus fertilizers. Throughout the growing season, levels of nitrate nitrogen and mobile phosphorus increased progressively from the initial to the final stages. Initial nitrate nitrogen levels ranged from 50.0 to 60.0 mg/kg during germination, rising significantly by the fourth cutting. For instance, in NS Alfa treated with 60 kg/ha phosphorus, nitrate nitrogen levels increased from 61.5 mg/kg at germination to 70.4 mg/kg after the fourth cutting (Table 4). This pattern was consistent across all varieties, with the highest levels observed in treatments with 120 kg/ha phosphorus (Table 4).

The addition of phosphorus can influence soil nitrogen pools and cycling processes through various impacts on plant growth and microbial activity. For example, phosphorus application can reduce nitrogen leaching losses and retain more nitrogen in plant-soil ecosystems by promoting plant and microbial growth and nitrogen uptake (Baral et al., 2014; Chen et al., 2017). However, it can also increase nitrogen loss through gaseous emissions, such as N_2O, by stimulating nitrification and denitrification processes (Mehnaz et al., 2019; Mori et al., 2013). In phosphorus-limited ecosystems, reductions in N_2O emissions have been observed due to a decline in NO3− availability and reduced denitrification (Chen et al., 2016; Mori et al., 2014; Yu et al., 2017).

Table 4. The effect of phosphorus fertilizers on the amount of nitrate nitrogen (mg/kg) in light chestnut soil of alfalfa crops

Treatment	Variety	Germination	1st Cutting	2nd Cutting	3rd Cutting	4th Cutting	Average
Control	NS Alfa	50.4	52.0	59.2	62.3	66.5	58.0
	VS Banat	55.3	50.0	62.0	65.3	68.0	60.1
	Mediana	50.7	55.8	60.0	62.3	65.0	58.8
	Nera	55.8	60.0	64.0	67.4	70.9	63.5
	Niagara	55.4	58.7	59.2	62.0	68.0	60.5
	Kokoray	53.2	57.0	62.0	65.3	68.0	61.1
P60	NS Alfa	61.5	62.4	65.7	67.0	70.4	65.4
	VS Banat	60.0	66.0	67.7	70.0	75.2	68.7
	Mediana	67.5	69.5	71.5	75.0	78.4	72.2
	Nera	61.0	64.0	66.0	68.8	75.5	67.1
	Niagara	62.0	65.0	68.7	70.0	75.2	68.2
	Kokoray	58.0	61.0	67.0	70.9	78.4	66.9
P90	NS Alfa	68.2	70.0	73.7	71.5	75.0	71.6
	VS Banat	65.5	75.0	76.8	77.5	80.5	75.1
	Mediana	65.2	70.2	75.7	77.4	82.6	74.2
	Nera	65.8	71.5	75.0	78.2	80.2	74.1
	Niagara	68.5	70.0	77.2	74.5	80.5	74.2
	Kokoray	64.5	68.5	76.0	77.0	82.6	73.7

Higher plant and microbial nitrogen uptake following phosphorus addition can also enhance biological nitrogen fixation (Ament et al., 2018; Houlton et al., 2008) and microbial nitrogen mining from soil organic matter (Fisk et al., 2014), thus improving ecosystem nitrogen input and cycling. Conversely, some studies have shown that phosphorus addition has no significant impact on the soil total nitrogen pool and nitrogen availability (McLaren and Buckeridge, 2019; Scott et al., 2015), while others have found a decrease in the total nitrogen pool and nitrogen availability, which was attributed to higher plant uptake and assimilation rates compared to litter-decomposition return rates (Stiles et al., 2017; Yu et al., 2017).

Similarly, mobile phosphorus levels in the soil also showed a marked increase with the application of phosphorus fertilizers. For instance, in the control plots, the mobile phosphorus content ranged from 25.8 to 28.0 mg/kg across the varieties during germination, indicating an average phosphorus supply level. However, in plots treated with 60 kg/ha of phosphorus, the mobile phosphorus levels increased to 23.3-26.5 mg/kg. Further application of 90 kg/ha of phosphorus resulted in mobile phosphorus levels ranging from 27.2 to 31.9 mg/kg (Table 5).

Table 5. The effect of phosphorus fertilizers on the amount of mobile phosphorus (mg/kg) in the light chestnut soil in the alfalfa field

Treatment	Variety	Germination	1st Cutting	2nd Cutting	3rd Cutting	4th Cutting	Average
Control	NS Alfa	26.2	22.5	19.0	18.0	15.5	20.2
	VS Banat	27.4	21.7	19.0	18.5	16.5	20.6
	Mediana	28.0	25.0	23.0	20.0	18.0	22.8
	Nera	27.0	24.0	20.0	20.0	17.0	21.6
	Niagara	25.8	23.4	20.0	17.0	16.5	20.5
	Kokoray	27.0	25.6	22.0	20.5	18.2	22.7
P60	NS Alfa	28.3	25.8	23.5	21.2	20.0	23.8
	VS Banat	29.7	24.8	23.0	20.5	18.5	23.3
	Mediana	30.3	28.2	26.2	24.5	23.0	26.4
	Nera	29.5	25.4	24.0	21.0	20.0	24.0
	Niagara	28.6	27.4	22.5	20.0	18.5	23.4
	Kokoray	29.0	27.5	25.0	19.5	23.0	24.8
P90	NS Alfa	33.1	30.0	26.3	24.0	23.0	27.3
	VS Banat	37.0	28.5	25.7	23.0	22.0	27.2
	Mediana	35.5	33.0	30.0	27.6	26.5	30.5
	Nera	36.7	34.7	31.2	30.4	26.5	31.9
	Niagara	35.5	35.0	24.3	22.5	22.0	27.9
	Kokoray	35.4	32.2	28.7	26.0	26.5	29.8

The results indicated distinct patterns in phosphorus availability influenced by both the applied P fertilizer doses and variety of the alfa alfa plants. Similarly, studies conducted by Medinski et al. (1998), Wu et al. (2020), Wang et al. (2022), Zhaksybayev et al. (2022) and Islamzade et al (2023) have determined that increasing application rates of chemical fertilizers to the soil result in both increased crop yields and improved phosphorus content in the soil.

Conclusion

The study conclusively demonstrated the critical role of phosphorus fertilization in enhancing both the yield and quality of alfalfa crops grown in light chestnut soils. Over the three-year period from 2013 to 2015, it was evident that increasing levels of phosphorus (60, 90, and 120 kg/ha) significantly improved various growth parameters. The yield data highlighted that phosphorus application markedly increased alfalfa productivity across all varieties. The highest efficiency was observed at the 120 kg/ha phosphorus level, where yields saw an increase of up to 34% for certain varieties such as Nera. This finding confirms that phosphorus is vital for root development and energy transfer in plants, leading to enhanced biomass production.

In terms of quality, the application of phosphorus fertilizer positively impacted the nutritional content of alfalfa hay. Increases in crude and digestible protein, fat, and carotene content were observed across all varieties with the highest application rate. This indicates that phosphorus not only boosts yield but also enhances the feed value of alfalfa, making it more beneficial for livestock. Furthermore, the study revealed that phosphorus fertilizer significantly improves the availability of nitrate nitrogen and mobile phosphorus in the soil. This enhanced nutrient availability supports better growth and productivity of alfalfa.

Overall, the application of 120 kg/ha phosphorus was identified as the most effective rate for achieving the highest improvements in yield and quality. The study underscores the multifaceted benefits of phosphorus fertilization in alfalfa cultivation. By optimizing phosphorus application rates, farmers can achieve significant improvements in both yield and quality of alfalfa, while also enhancing soil health. Future research should aim to refine these application rates and investigate the long-term implications of continuous phosphorus use, ensuring sustainable and productive alfalfa farming practices.

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