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Influence of fertilization on yield, nutritional and qualitative characteristics of potato tubers under different agro-climatic conditions in Armenia

A.O. Markosyan[1], M.H. Zadayan[2,*], S.K. Baghdasaryan[1], S.Z. Kroyan[3], S.A. Markosyan[4] and G.H. Gasparyan[1]

[1]Armenian National Agrarian University, Scientific Center of Soil Science, Agrochemistry and Melioration named after H. Petrosyan, 24 Admiral Isakov Ave, AM0004 Yerevan, Armenia
[2]Center for Agricultural Research and Certification, State Non-Commercial Organization of the Ministry of Economy of the Republic of Armenia, AM1139, v. Merdzavan, Armavir Marz, Yerevanyan highway 2nd deadlock, building 4, Armenia
[3]National University of Architecture and Construction of Armenia, Department of Engineering Geodesy, Teryan Str., 105, AM0009 Yerevan, Armenia
[4]Yerevan State University, Faculty of Biology, Department of Biology, 1 Alex Manoogian, AM0025 Yerevan, Armenia
[*]Correspondence: mhzadayan@gmail.com

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Abstract. This study investigates the effects of mineral (N150P120K120, 'Control-Treatment 1') and organo-mineral fertilization (with 20 t ha^{-1} of farmyard manure (FYM), 'Treatment 2', and 40 t ha^{-1} of FYM, 'Treatment 3') on the yield, nutritional value, and quality of potato (*Solanum tuberosum L.*) tubers under different agro-climatic conditions in Armenia. Field trials were conducted in two contrasting regions: Dasht village (Ararat Plain, 850 m a.s.l.) with cultivated irrigated meadow-fulvous soils, and Vahan village (Gegharkunik Highlands, 2000 m a.s.l.) with mountain black soils (chernozems). The research measured tuber yield, dry matter, starch, vitamin C, and protein content over three years (2019–2021).

Application of T3 (NPK + 40 t ha^{-1} FYM) significantly improved all measured indicators. Yield increased by up to 28%, dry matter by 10.8%, starch by 12.0%, vitamin C by 13.4%, and protein content by 14.4%. Climate conditions also had a significant impact on tuber productivity and composition. In chernozems, compared to irrigated meadow-fulvous soils, yield increased by 15.1–21.6%, and the content of dry matter, starch, and vitamin C increased by 3.1–8.7%. However, protein content was higher in the irrigated meadow-fulvous soils by 3.4–5.2%.

These results demonstrate the importance of fertilization strategies tailored to specific agroecological zones and climatic trends, particularly in the context of climate change adaptation.

Key words: agro-climatic conditions, dry matter, farmyard manure, growth conditions, mineral and organic fertilization, potato, protein content, starch, tuber yield and quality, vitamin C.

INTRODUCTION

Potato (*Solanum tuberosum* L.) is one of the most widely cultivated and nutritionally significant crops worldwide. It is a rich source of carbohydrates, vitamin C, potassium, and moderate amounts of high-quality protein, making it a key component of food security and human nutrition.

In Armenia, potato is cultivated across a wide range of agro-climatic zones, from lowland plains to high-altitude regions. Despite its importance, both yield and tuber quality often remain suboptimal, primarily due to inappropriate fertilization practices and the declining fertility of soils under intensive cropping systems (Hayrapetyan, 2000; FAO, 2010).

A growing body of research has confirmed that balanced mineral and organic fertilization is essential for improving both tuber yield and biochemical composition. The combined use of farmyard manure (FYM) and mineral fertilizers significantly enhances the accumulation of dry matter, starch, vitamin C, and protein in potato tubers (El-Sayed et al., 2015; Ahmed et al., 2019; Gelaye, 2023). Moreover, this integrated approach positively affects storability and marketability of tubers (Lombardo et al., 2013; Brazinskienė et al., 2014).

Global demand for potatoes is projected to increase further, driven by population growth and the need for affordable, nutrient-dense food sources (Lutaladio & Castaldi, 2009; Devaux et al., 2014; Jennings et al., 2020). At the same time, environmental sustainability and resource conservation are becoming increasingly urgent priorities for global agriculture (Ayupov et al., 2014).

Potato has high potential as a food crop, as it provides a nutritionally valuable yield per unit area within a relatively short growing season (< 120 days), compared to cereal crops such as maize (Hirpa et al., 2010). The nutritional value of potatoes depends on the balance of organic and mineral constituents necessary for human health. Depending on the variety, potato tubers contain 15–35% dry matter, of which 80–85% is starch and up to 3% protein (Danilchenko et al., 2008; Ayupov et al., 2014), along with up to 31 mg 100 g^{-1} (fresh weight) of vitamin C (Bista & Bhandari, 2019). Potatoes are also rich in vitamin B6, potassium, and various antioxidants that strengthen immunity (Camire et al., 2009; Pacier & Martirosyan, 2015; Beals, 2019; Mattoo et al., 2022; Xu et al., 2023).

Potato yield and quality are strongly influenced by variety, environmental conditions, and agronomic practices (Bártová et al., 2013; Lombardo et al., 2013; Brazinskienė et al., 2014; Novikova, 2021). Potatoes are highly sensitive to soil fertility, physical soil properties, and the availability and balance of macro- and micronutrients (El-Sayed et al., 2015; Ahmed et al., 2019; Awad et al., 2022; Mancer et al., 2024). Fertilization strategies must therefore be designed to ensure that vegetative growth is supported while promoting the formation of tubers with desirable qualitative and nutritional characteristics (White et al., 2007; Koch et al., 2020; Naumann et al., 2020).

Among mineral nutrients, nitrogen plays a particularly significant role in potato production, influencing vegetative growth, tuber yield, chemical composition, and quality (Hopkins et al., 2008; Sincik et al., 2008; Zelalem et al., 2009; Abreham, 2022;

Harraq, 2022). However, the positive effects of nitrogen occur only up to a certain threshold, beyond which excessive application fails to further increase yield and may even reduce tuber quality (Love et al., 2005; Olivier et al., 2006; Zebarth and Rosen, 2007; Eremeev et al., 2009). Overuse of nitrogen can also cause nitrate accumulation in tubers, posing serious health risks, including carcinogenic effects (Atafar, 2010; Chen et al., 2017; Alengebawy et al., 2021; Jovovic et al., 2021).

To address these challenges, researchers advocate combining mineral and organic fertilizers (Jhangiryan et al., 2024) to enhance soil physical, mechanical, biochemical, and fertility properties (Ahmed et al., 2019; Miskoska-Milevska et al., 2020; Kuht et al., 2023). Organic fertilizers improve soil water-holding capacity by approximately 17% and increase soil porosity by about 12% (Setiyo et al., 2021), creating conditions favorable for root and tuber development. Improved nutrient balance also promotes protein accumulation in potato tubers (Naghdi et al., 2022; Martirosyan et al., 2024).

Research and production data indicate that potato fertilization practices must be tailored to specific soil types and climatic conditions to achieve optimal productivity and quality (Sintsova & Lyskova, 2020; Tamrazov, 2021). Potatoes require extended daylight hours and high light intensity, as well as ample moisture, particularly during tuberization and flowering stages. They grow best in fertile, light-textured soils. The optimal temperature range for photosynthesis and tuber development is 20–25 °C (Jiménez et al., 2008; Andayani & Maryam, 2019; Setiyo et al., 2021). Physiological processes weaken at 26–29 °C and cease entirely above 33 °C (Sun et al., 2017; Wang et al., 2018; Obiero et al., 2020).

Soil temperature and moisture are critical environmental factors affecting tuber yield and quality. Potatoes grown at 85% relative humidity produce higher yields than those grown at 50% humidity (Setiyo et al., 2021). In high-altitude, cooler climates, tubers tend to accumulate more dry matter and vitamin C, whereas in warmer, drier regions, protein content is higher, largely due to increased nitrogen uptake and metabolism (FAO, 2010; Minasyan, 2015; Raymundo et al., 2018; Jennings et al., 2020; Jovovic et al., 2021).

Study objectives

This study aims to:

1. Evaluate the effects of mineral and organo-mineral fertilization under two contrasting agro-climatic and soil conditions - irrigated meadow-fulvous soils of the Armavir region (Dasht) and mountain chernozems of the Gegharkunik region (Vahan) - on the yield and nutritional quality of potatoes in Armenia.

2. Develop region-specific sustainable fertilization strategies to improve potato production.

3. Elucidate the relationships between growth conditions, yield, and tuber quality characteristics, thereby addressing a knowledge gap in scientific research on potato production in lowland versus highland agro-ecological zones.

MATERIALS AND METHODS

Research sites

Field trials were conducted in two villages. In Vahan village (Gegharkunik region, 2000 m a.s.l.), mountain carbonated chernozems predominate. These soils have a lumpy-granular structure and a loamy texture. Organic carbon content is quite high, reaching 3.5–4.7% in the upper horizons of uncultivated soils. However, they are deficient in mobile nutrients—nitrogen, weakly to moderately supplied with phosphorus, and weakly to moderately supplied with potassium. The Ca content in these soils is 39.0 mg eq per 100 g of soil, and the mg content is 9.3 mg eq per 100 g of soil. The soil pH ranges from 7.0 to 7.2 (Soils of the Armenian SSR, 1976).

According to the Köppen climate classification, the region has a temperate continental climate classified as Dfb (Köppen-Geiger, 2024). The average annual air temperature varies between 5.5–6.0 °C, with 16.5 °C during July–August. The sum of temperatures above 0 °C is 2,600 °C, and above 10 °C is 2,100 °C. The average annual precipitation ranges between 400–500 mm, with 280 mm falling during the warm months. Maximum precipitation occurs in late spring and early summer (Melkonyan et al., 2004).

Dasht village (Armavir region, 800 m a.s.l.) is characterized by hot, dry summers and irrigated meadow-fulvous soils. The relief of the Armavir region is flat. Irrigated meadow-fulvous soils are heavy clayey-granular in texture, with weak silty-granular structure and 3.7% carbonate content. The organic carbon content in the upper horizons varies between 0.9–1.2%. These soils are poorly supplied with mobile nitrogen, moderately to well supplied with phosphorus and potassium. The Ca content in these soils is 29.8 mg eq per 100 g of soil, and the mg content is 8.2 mg eq per 100 g of soil. The soil pH varies between 7.8 and 8.5 (Soils of the Armenian SSR, 1976).

According to the Köppen climate classification, the region has a semi-arid temperate continental climate classified as BSk (Köppen-Geiger, 2024). The climate is strictly arid and continental. The average annual air temperature reaches 11.8 °C, with absolute minimum temperatures of -27 to -30 °C and maximum temperatures of +39 to +40 °C. The sum of temperatures above 0 °C is 4,500–4,800 °C, and above 10 °C is 4,000–4,200 °C. The average annual precipitation varies between 250–280 mm, with maximum precipitation occurring in May (Melkonyan et al., 2004).

Soil sampling and analysis

To assess the agrochemical properties of soils, soil samples were collected before fertilization and again at flowering from two pits per experimental field at a depth of 0–30 cm. Soil pH was determined by the electropotentiometric method, organic carbon content by the Tyurin method, available nitrogen by the Tyurin-Kononova method, P_2O_5 by the Machigin method, and K_2O by the Maslova method (Arinushkina, 1970; Faithfull, 2002).

During the flowering stage, soil and air temperatures, and relative air humidity (in both interplant and interrow spaces) were measured. Soil moisture was determined from soil samples taken at 30 cm depth. Soil surface temperature at 15 cm depth was measured with a Savinov thermometer, and air temperature and humidity were measured with an

MB-4M aspiration psychrometer. Measurements were performed three times daily at 8:00, 13:00, and 19:00. Soil moisture was determined by drying samples in an oven until reaching a constant weight.

Experimental design

Field experiments were conducted from 2019 to 2021 using a randomized complete block design (RCBD) (Bush, 2023) with three replicates. The plot size was 50 m² (Matevosyan & Gyulkhasyan, 2000). Tubers (50–80 g) were planted at a spacing of 70×30 cm. The test variety was *Impala* (*Solanum tuberosum* L. cv. Impala), an early maturing, high-yielding Dutch variety that produces large (80–160 g), oval-shaped tubers with smooth yellowish skin and light yellow flesh. Fertilization treatments were:

1. T1 (Control): NPK (N150P120K120) mineral only.
2. T2: NPK + 20 t ha^{-1} of well-rotted farmyard manure (FYM).
3. T3: NPK + 40 t ha^{-1} FYM.

The inorganic fertilizers used were ammonium nitrate (N, 34% active ingredient), triple superphosphate (P, 50% active ingredient), and potassium chloride (K, 60% active ingredient).

Planting in Dasht village was performed in the third week of March and in Vahan village in the third week of May, using pre-germinated tubers. During the research years, tuber harvesting was carried out after the widespread natural death of the tops: in Dasht village in the last week of June, and in Vahan village in the third week of September.

Crop Management

Soil cultivation and plant care followed standard procedures for the respective climatic conditions. Irrigation was applied only in Dasht. During the growing season, insect pests and late blight were monitored, but no systemic pesticide applications were necessary; only standard cultural practices (hilling, irrigation, crop rotation) were used. In autumn, before deep plowing, the experimental plots were fertilized with mature FYM and the full amount of potassium and two-thirds of phosphorus fertilizers. During spring planting, the remaining phosphorus and two-thirds of the nitrogen were applied. The final nitrogen application was provided during the first loosening as top dressing.

Measurements and data collection

Phenological observations included the onset (10%) and completion (75%) of tuber germination, stolon formation, flowering, and tuber maturity. Growth and development parameters were measured at flowering on 25 plants per treatment, including plant height, number of stems, number of leaves, leaf area, weight, number of stolons, tuber formation efficiency, and tuber number.

Yields were determined by harvesting and weighing individual plots. Yield was recorded from each treatment, per replicate of 25 plants. Tuber samples were collected from each treatment to determine dry matter, starch, vitamin C, and protein content.

Dry matter content was determined by oven-drying at 105 °C, starch content by the specific gravity method (Arinushkina, 1970), total protein by the Kjeldahl method (N × 6.25), and vitamin C by iodometric titration (Dioha, 2011). Leaf area was measured using Easy Leaf Area software.

Statistical analysis

Data analysis was performed using R (v4.5.0). The following libraries were used:

- *tidyverse* (including dplyr) for data manipulation and summarization,
- *dplyr* for grouping and summarizing data,
- *agricolae* for Least Significant Difference (*LSD*) tests after *ANOVA*,
- *knitr* and *kableExtra* for professional table generation,
- *cor.test* (from base R) for Pearson's correlation analysis,
- *ggpubr* for visualizing correlation results.

Significance was tested using two-way *ANOVA*, and treatment means were compared using *LSD* at $p < 0.05$. Results are reported as means ± standard error (SE).

RESULTS AND DISCUSSION

Agro-climatic and soil conditions of the experimental sites

The two areas differed significantly in climate and soil characteristics. Dasht (Ararat Valley) is characterized by hot summers (> 30 °C) and low precipitation, while the high-mountainous Vahan remains cool (< 25 °C) with abundant precipitation, conditions that promote larger tuber size and greater starch accumulation. Monthly average temperature and precipitation data during the growing seasons (2019–2021) are summarized in Fig. 1, based on the National Hydrometeorological Service database (2021). Meteorological comparisons show that precipitation in Vahan during the growing season is 2.8 times greater than in Dasht (321 mm total). Conversely, average monthly temperatures in Vahan are about 9 °C lower, averaging 12.9 °C.

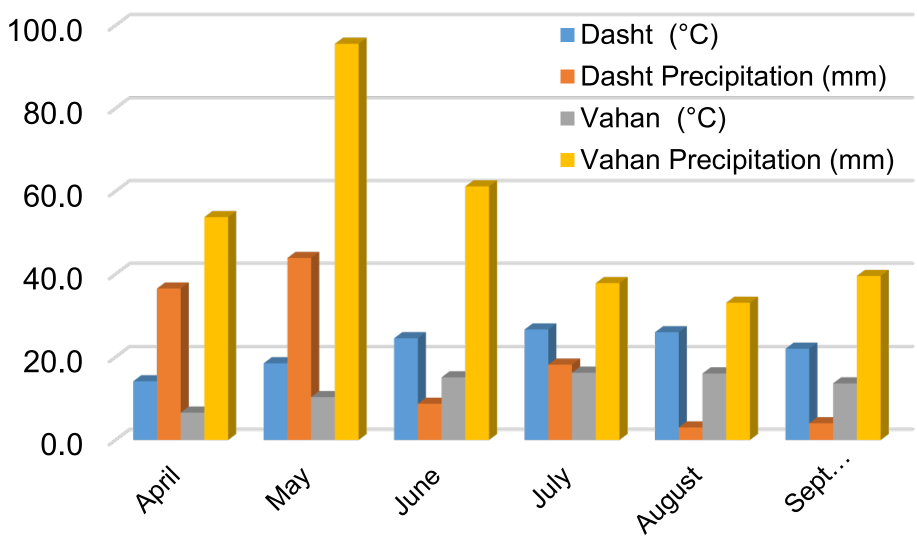

Figure 1. Monthly precipitation (mm) and average air temperature (°C) in Dasht and Vahan villages during the 2019–2021 vegetation seasons.

Using the Köppen-Geiger climate classification, Dasht is classified as BSk (semi-arid steppe), while Vahan is classified as Dfb (humid continental, warm summer) (Figs 2, 3) (Köppen-Geiger, 2024).

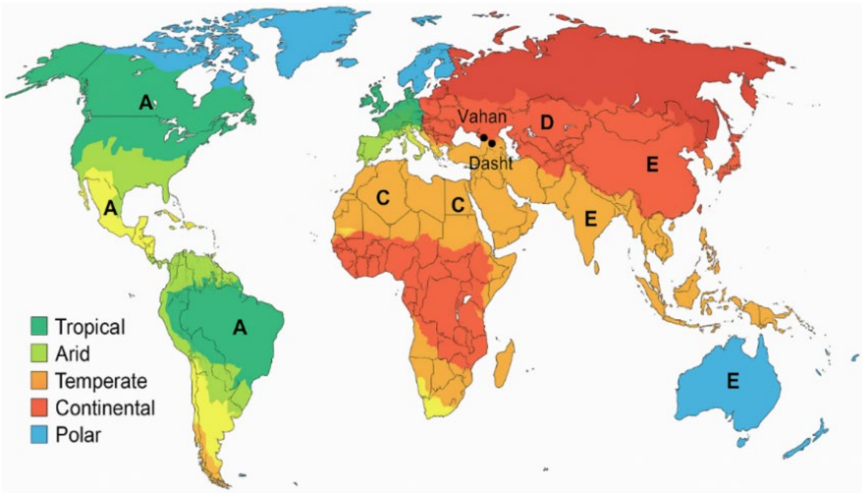

Figure 2. Climatic classification of the study areas according to the Köppen-Geiger system (world map). Source: Beck et al., *Scientific Data* 5:180214 (2018).

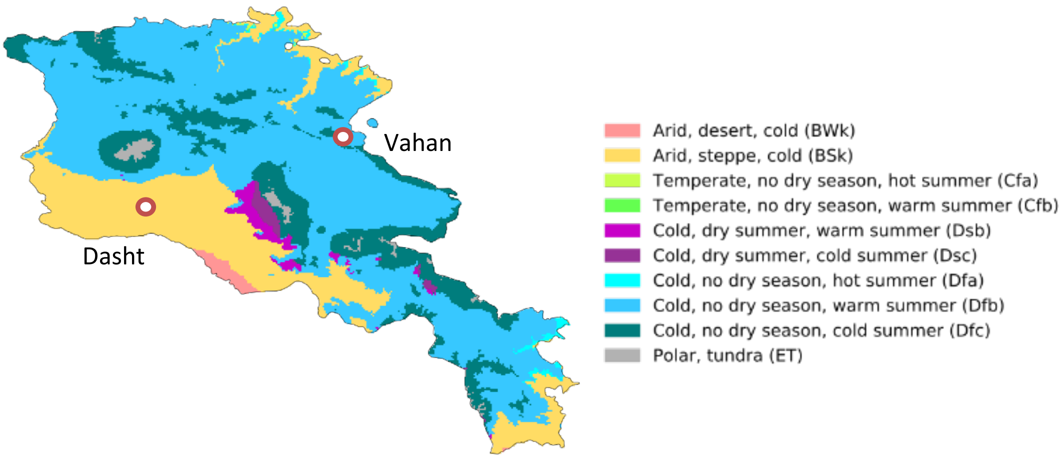

Figure 3. Climatic classification of the study areas according to the Köppen-Geiger system (Armenia map). Source: Beck et al., *Scientific Data* 5:180214 (2018).

Table 1 shows that the soils differed notably before planting and during flowering. In Dasht (irrigated meadow-fulvous soils), humus content was 2.15–2.25%, mobile nitrogen 3.58–3.98 mg 100 g^{-1} soil, phosphorus 2.22–2.33 mg 100 g^{-1} soil, potassium 38.25–38.61 mg 100 g^{-1} soil, and pH 8.0–8.2. In contrast, Vahan's mountain chernozems had humus contents of 4.39–4.53%, mobile nitrogen 5.75–5.91 mg 100 g^{-1}, phosphorus 4.8–4.9 mg 100 g^{-1}, potassium 15.5–20.9 mg 100 g^{-1}, and pH 7.0–7.2. Fertilization, particularly with combined organo-mineral inputs, significantly improved soil nutritional properties, especially under T3 treatment (NPK + 40 t ha^{-1} FYM).

Climatic differences had a direct impact on potato growth, particularly during flowering and tuber bulking. In Vahan, higher precipitation and moderate temperatures contributed to increased assimilate transport into tubers, while in Dasht, water stress limited their accumulation. Similar results have been reported by Rykaczewska (2015), Singh et al. (2019), Djaman et al. (2021), Gouerou et al. (2025), Molmann and Johansen (2025).

Table 1. Agrochemical properties of soils in Dasht and Vahan experimental sites before planting and at the flowering stage (average of 2019–2021)

Experimental site, village	Fertilization	Before fertilization					During flowering				
		Organic carbon content (%)	pH	Mobile nutrients, mg in 100g of soil			Organic carbon content (%)	pH	Mobile nutrients, mg in 100g of soil		
				N	P_2O_5	K_2O			N	P_2O_5	K_2O
Dasht	Control (Treatment 1)	1.3	8	3.85	2.33	38.61	1.6	8	5.12	4.08	40.01
	Treatment 2	1.25	8.1	3.58	2.22	38.39	1.88	8.1	7.58	6.12	42.09
	Treatment 3	1.28	8.2	3.98	2.25	38.25	2.12	8.3	8.98	7.95	43.25
Vahan	Control (Treatment 1)	2.55	7	5.75	4.9	15.5	2.64	7	7.85	6.54	23.8
	Treatment 2	2.58	7.1	5.84	4.84	18.8	3.2	7.2	9.78	8.89	25.5
	Treatment 3	2.63	7.2	5.91	4.8	20.9	3.74	7.3	11.25	12.54	28.8

Soil temperature dynamics

According to Table 2, fertilization influenced soil surface temperatures. In Dasht, during mornings (8:00), the control treatment registered soil temperatures 0.7–1.1 °C lower compared to T3, while at midday (13:00) and evening (19:00), the control registered 0.8–2.4 °C higher temperatures. The increase in soil temperature under organic fertilization is attributed to the darker color and organic matter content, which improve soil thermal properties and enhance biological activity (Konen et al., 2003; Kumar et al., 2020). Similar differences were observed between inter-row and inter-plant areas, as plant canopy coverage reduces soil exposure.

Table 2. Effect of fertilization on soil surface temperature (°C) during flowering stage

Experimental site, village	Fertilization	8^{00}		13^{00}		19^{00}	
		Interplant	Interline	Interplant	Interline	Interplant	Interline
Dasht	Control (Treatment 1)	15.3	15.0	21.8	23.4	19.2	19.0
	Treatment 2	15.8	15.4	20.1	22.6	19.0	19.1
	Treatment 3	16.4	15.7	19.4	22.0	18.5	18.3
Vahan	Control (Treatment 1)	12.8	12.3	17.2	18.8	15.9	15.2
	Treatment 2	13.1	13.2	17.0	18.1	16.3	15.5
	Treatment 3	13.4	13.4	16.5	17.5	16.5	16.0

Comparable patterns were observed at a soil depth of 15 cm (Table 3). In both Dasht and Vahan, soil temperatures under treatment T3 were consistently more stable compared to the control. These results align with previous findings indicating that organic amendments buffer soil thermal fluctuations (Lal, 2020; Kumar et al., 2021).

In Dasht village, at 15 cm depth during morning measurements (8:00), the control treatment showed temperatures 0.4–1.0 °C lower in interplant spaces and 0.4–0.9 °C lower in interline spaces compared to treatment T3 (NPK + 40 t ha^{-1} FYM). At 13:00, the control plots were 0.5–1.0 °C higher in interplant spaces and 0.7–1.2 °C higher in interline spaces relative to T3. In the evening (19:00), differences were 0.4–1.6 °C and 0.3–0.8 °C, respectively.

Table 3. Effect of fertilization on soil temperature at a depth of 15 cm (°C) during the flowering stage

Experimental site, village	Fertilization	8 00		13 00		19 00	
		Interplant	Interline	Interplant	Interline	Interplant	Interline
Dasht	Control (Treatment 1)	16.5	16.9	18.5	19.7	18.4	17.0
	Treatment 2	16.9	17.3	18.0	19.0	18.0	16.7
	Treatment 3	17.5	17.8	17.5	18.5	16.8	16.2
Vahan	Control (Treatment 1)	14.0	13.7	16.5	17.9	16.0	16.8
	Treatment 2	14.3	14.1	16.3	17.2	15.8	16.5
	Treatment 3	14.5	14.2	16.1	17.0	15.8	16.0

A similar pattern was observed in Vahan village. At 8:00, soil temperatures under the control were 0.3–0.6 °C and 0.9–1.1 °C lower in interplant and interline spaces, respectively. By 13:00, they were 0.2–0.7 °C and 0.7–1.3 °C higher, and by 19:00, 0.4–0.6 °C and 0.3–0.8 °C higher compared to treatment T3.

Additionally, climatic differences between the two locations caused significant variations independent of fertilization. In Dasht, the soil surface temperature in potato rows, interplant, and interline spaces was 2.5–4.6 °C higher than in Vahan village.

Observations indicate that the combined application of mineral and organic fertilizers had a pronounced effect on both soil moisture content and relative air humidity within potato crops. This effect is primarily linked to the increase in soil organic matter, which enhances soil structure and water-holding capacity by improving its physical properties (Ozlu et al., 2019; Lal, 2020; Kumar et al., 2021; Acar et al., 2025).

The role of relative air humidity is also crucial for potato growth and development. High relative humidity levels have been shown to support optimal physiological processes in potato plants (Setiyo et al., 2021). Therefore, in the present study, humidity was measured both between plants (interplant spaces) and between rows (interline spaces) to capture microclimatic variations.

In Dasht village, under control conditions (mineral fertilization only, N150P120K120), the relative air humidity at 8:00 was 55% in both interplant and interline spaces. By mid-afternoon (13:00), humidity dropped to 45% and 48%, respectively, before rising again to approximately 53% by 19:00.

Under T3 treatment (N150P120K120 + 40 t ha^{-1} FYM), relative humidity increased by 9–13% in the morning and 7–10% in the afternoon compared with the control, demonstrating the positive effect of FYM on microclimate regulation.

In Vahan village, a similar diurnal pattern was recorded. However, the overall relative humidity values were higher than in Dasht, with T3 treatment exceeding the control by approximately 8–9% throughout the day.

In addition to atmospheric humidity, soil moisture content showed a clear improvement under organo-mineral fertilization. Across both study sites, T3 treatment resulted in an average increase of 3.8% compared to the control, confirming the water-retention benefits of organic amendments.

It is noteworthy that the relative air humidity in Dasht was consistently 20–23% lower than in Vahan under similar fertilization conditions, reflecting the warmer and drier microclimate of the Ararat Valley compared to the cooler, more humid highlands of Chambarak (Table 4).

Table 4. The effect of soil and climatic conditions and fertilization on changes in relative air and soil humidity (flowering stage, %)

Experimental site, village	Fertilization	8 00		13 00		19 00		13 00
		Interplant	Interline	Interplant	Interline	Interplant	Interline	Soil moisture at a depth of 30 cm, %
Dasht	Control (Treatment 1)	55	55	48	45	53	53	22.5
	Treatment 2	62	64	50	52	57	56	24.7
	Treatment 3	68	65	60	55	62	60	25.7
Vahan	Control (Treatment 1)	75	75	70	68	70	70	18
	Treatment 2	82	83	73	75	75	72	19.8
	Treatment 3	84	84	78	76	78	76	21.8

The results of the study demonstrated that variations in plant growth conditions, influenced by both fertilization and agro-climatic factors, had a direct effect on the growth, development, and yield formation of potato plants, as well as on the qualitative characteristics of the tubers.

As shown in Table 5, soil and climatic conditions, together with fertilization, significantly affected the transition between potato phenological phases and the overall duration of the growing season.

Table 5. Duration of potato phenophase transition depending on fertilization and climatic conditions

Experimental site, village	Fertilization	Duration of development stages, days			
		Planting to germination	Germination to cocooning	Cocooning to flowering	From flowering to natural death of the tops
Dasht	Control (Treatment 1)	21	23	15	33
	Treatment 2	21	24	18	36
	Treatment 3	20	23	19	38
Vahan	Control (Treatment 1)	26	26	16	33
	Treatment 2	27	27	17	35
	Treatment 3	27	28	19	38

According to field observations, in Dasht village, the period from planting to emergence lasted 20–21 days, whereas in Vahan village, where the climate is cooler, this period extended to 26–27 days.

In Dasht, the time span from emergence to natural senescence of the potato tops was 71 days under the control treatment and 80 days under the high fertilization treatment (T3: N150P120K120 + 40 t ha^{-1} FYM).

Similarly, in Vahan, the duration was 75 days for the control and 85 days under T3.

These results indicate that high fertilization rates prolonged the vegetation period by 9–10 days, irrespective of the location or prevailing agro-climatic conditions. The extended vegetation period reflects improved nutrient availability and more favorable physiological conditions for plant development, ultimately contributing to higher yields and better tuber quality (Table 5).

The combined application of mineral and organic fertilizers created a more favorable environment for the growth and development of both the aboveground and belowground organs of potato plants.

In Vahan village, intensive fertilization (T3: N150P120K120 + 40 t ha^{-1} FYM) resulted in notable improvements compared to the control. Specifically, stem height increased by 14.0 cm, the number of stems by 2.6, the number of leaves by 21, leaf biomass by 123.7 g, and leaf area by 1,894.3 cm².

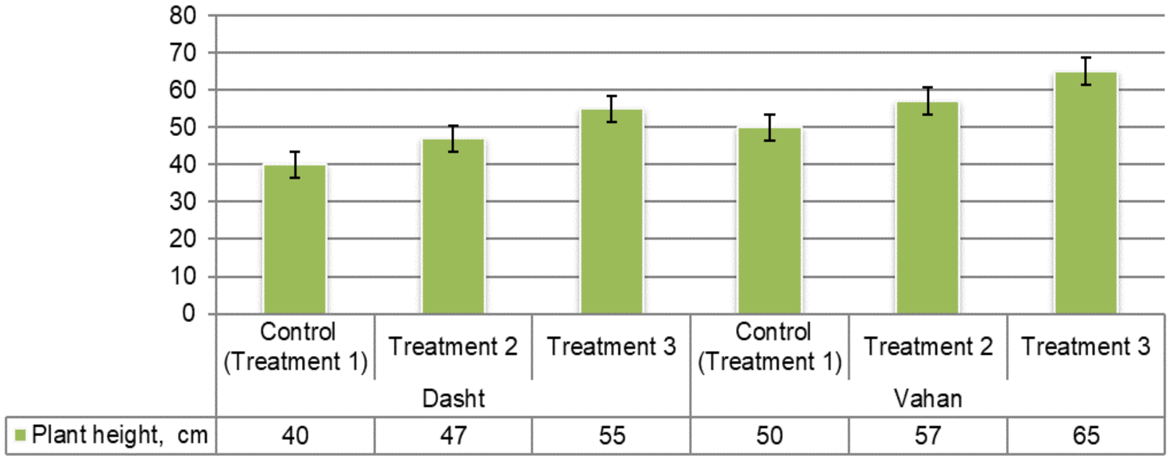

Figure 4. The height of potato plants depending on fertilization and climatic conditions during the flowering stage. $LSD_{0.5}$ = 3.27.

In Dasht village, the values for these parameters were slightly higher, with respective increases of 14.3 cm, 2.3 stems, 19 leaves, 95.0 g of leaf biomass, and 2009.1 cm² of leaf area (Fig. 4, Table 6).

Table 6. Growth and development of aboveground organs of potato depending on fertilization and climatic conditions (during flowering stage)

Experimental site, village	Fertilization	One bush			
		Stems per plant, pcs.	Leaves per plant, pcs.	Leaf weight, g	Leaf area, cm^2
Dasht	Control (Treatment 1)	4.7	79	245.3	5,086.1
	Treatment 2	6	90.3	296.7	5,993.4
	Treatment 3	7	98	340.3	7,095.2
Vahan	Control (Treatment 1)	5.7	81	340.3	6,753.6
	Treatment 2	7.3	87.7	414.3	7,314.7
	Treatment 3	8.3	102	464	8,647.9
LSD_{05}		0.78	3.35	4.97	55.65

These results clearly demonstrate that higher levels of organo-mineral fertilization promote more vigorous vegetative growth by improving nutrient availability and enhancing soil moisture retention. The increase in leaf area and biomass is especially important, as it directly contributes to higher photosynthetic capacity, ultimately supporting tuber bulking and yield formation.

Soil and climatic conditions also had a significant effect on the formation of the aboveground biomass of potato plants. Under comparable fertilization treatments, potato plants grown in Vahan village were, on average, 10 cm taller, with 1.0–1.3 more stems and 2–4 additional leaves per plant compared to those grown in Dasht village. These additional leaves contributed to a higher total biomass, weighing 95.0–123.7 g, and covered 1,552.7–1,667.5 cm^2 more leaf surface area than plants from Dasht.

The influence of fertilization was also clearly evident in the development of the underground organs of potato plants. In Vahan, under T3 treatment (N150P120K120 + 40 t ha^{-1} FYM), plants exhibited markedly vigorous growth, producing 5.6 more stolons and 4.0 more tubers per bush compared to the control. Furthermore, stolon efficiency was 2.1% higher than in the control plots.

In Dasht village, the response to T3 was slightly lower but still substantial, with increases of 3.6 stolons, 3.5 tubers per bush, and a 2.0% improvement in stolon efficiency relative to the control (Table 7).

Table 7. Growth and development of underground organs of potato depending on fertilization and climatic conditions during the flowering stage

Experimental site, village	Fertilization	Quantity pcs., bush		Stolon efficiency, %
		Stolon	Tuber	
Dasht	Control (Treatment 1)	27.9	14.8	53
	Treatment 2	28.6	16.2	56.6
	Treatment 3	31.5	18.3	58
Vahan	Control (Treatment 1)	28.1	16.5	58.7
	Treatment 2	30.4	18.3	59.5
	Treatment 3	33.7	20.5	60.8
$LSD_{0.5}$		2.28	2.01	

Notes:

- Values represent the mean of three replications ± standard deviation (SD)
- T1 – Control (mineral fertilizer only, N150P120K120)
- T2 – N150P120K120 + 20 t ha^{-1} FYM (farmyard manure)
- T3 – N150P120K120 + 40 t ha^{-1} FYM
- *Stolon efficiency* was calculated as the ratio of stolon number to tuber number per plant, expressed as a percentage (%)
- Differences between treatments were evaluated using $LSD_{0.5}$ test; values followed by different letters in the same column are significantly different ($p < 0.05$).

The combined application of mineral and organic fertilizers had a significant positive effect on potato yield. In Vahan village, yield under the high fertilization treatment (T3: N150P120K120 + 40 t ha^{-1} FYM) increased by 139.1 c ha^{-1} compared to the control. In Dasht village**,** the corresponding yield increase was 90.5 c ha^{-1}.

Soil and climatic conditions also exerted a substantial influence on yield performance. Across all treatments, Vahan consistently outperformed Dasht by 66–115 c ha^{-1}, which can be attributed to higher rainfall**,** moderate temperatures, and favorable moisture conditions in the highland area, compared with the hotter and drier conditions of the Ararat Valley (Figs 1 and 4).

The combined application of mineral and organic fertilizers had a positive effect on the qualitative composition of potato tubers, particularly by increasing the content of dry matter**,** starch**,** vitamin C, and proteins.

In Vahan village, under control conditions (T1: mineral fertilizer only), the tubers contained 21.3% dry matter, 13.3% starch, and 21.3% vitamin C. Under T2 and T3 treatments, where both mineral and organic fertilizers were applied, these indicators increased by 0.9–1.7%, 1.1–1.6%, and 1.5–2.6%, respectively, compared with the control.

Similarly, in Dasht village, the content of dry matter increased by 0.8–1.8%, starch by 1.0–1.4%, and vitamin C by 1.3–2.3% compared to the control treatment. These improvements suggest that organo-mineral fertilization enhances nutrient accumulation in tubers by improving soil nutrient availability and plant physiological processes (Table 8).

Table 8. The effect of fertilization on the qualitative characteristics of potato tubers under different climatic conditions

Experimental site, village	Fertilization	Dry matter, %	Starch, %	Vitamin C, mg per 100g	Protein, g per 100g
Dasht	Control (Treatment 1)	20.5	12.3	20.5	2.01
	Treatment 2	21.3	13.3	21.8	2.14
	Treatment 3	22.3	13.7	22.8	2.3
Vahan	Control (Treatment 1)	21.3	13.3	21.3	1.98
	Treatment 2	22.2	14.4	22.8	2.08
	Treatment 3	23	14.9	23.9	2.16
$LSD_{0.5}$		0.90	0.92	1.22	0.12

Notes:

- T1 – Control (mineral fertilizer only, N150P120K120)
- T2 – N150P120K120 + 20 t ha^{-1} FYM (farmyard manure)
- T3 – N150P120K120 + 40 t ha^{-1} FYM
- Values represent the mean of three replications ± standard deviation (SD)
- Differences between treatments were determined using the $LSD_{0.5}$ test; values followed by different letters in the same column indicate significant differences ($p < 0.05$).

Protein content

Protein content was less influenced by fertilization and was primarily determined by climatic conditions. In the relatively warmer and drier conditions of Dasht village, the protein content in potato tubers was higher compared to the cooler and more humid mountainous conditions of Vahan.

Regardless of the fertilization treatment, protein levels in Dasht fluctuated between 2.01–2.30%, whereas in Vahan they ranged from 1.99–2.16%. This suggests that higher temperatures and lower relative humidity promote increased nitrogen mineralization and protein synthesis in potato tubers.

Yield performance

Tuber yield was significantly affected by both fertilization and location. In both study sites, the T3 treatment (N150P120K120 + 40 t ha^{-1} FYM) produced the highest yields, reaching 639.6 c ha^{-1} in Vahan and 525.7 c ha^{-1} in Dasht (Fig. 5).

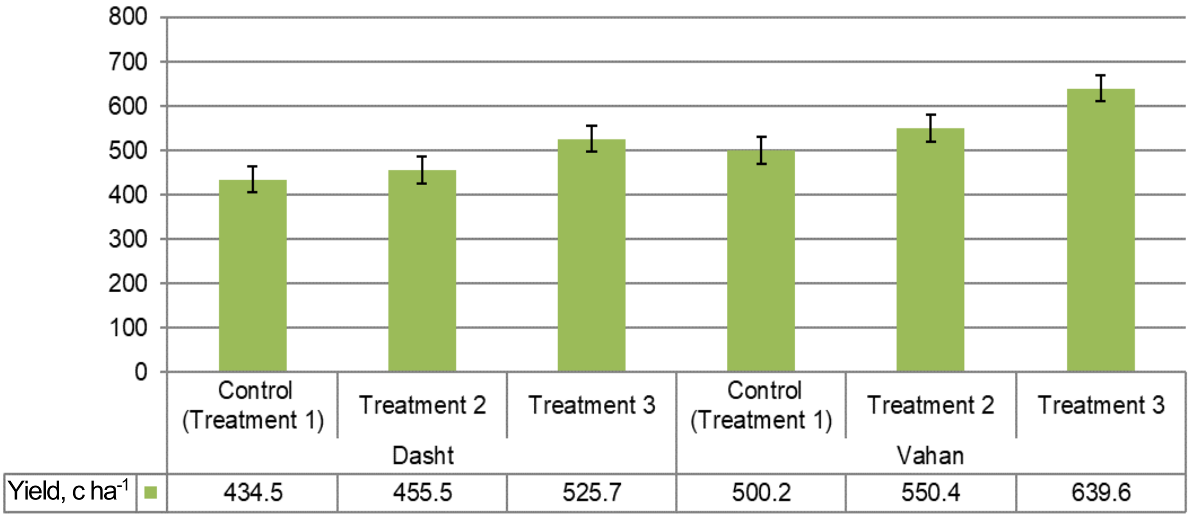

Figure 5. The effect of fertilization on potato yield under different climatic conditions. $LSD_{0.5}$ = 63.63.

Notes:

- T1 – Control (mineral fertilizer only, N150P120K120)
- T2 – N150P120K120 + 20 t ha^{-1} FYM (farmyard manure)
- T3 – N150P120K120 + 40 t ha^{-1} FYM
- Values represent the mean of three replications ± standard deviation (SD)
- Bars marked with different letters indicate significant differences between treatments according to *LSD* test at $p < 0.05$
- Yield is expressed in centners per hectare (c ha^{-1}).

Overall, yields in Vahan exceeded those in Dasht by 15.1–21.6%, reflecting the higher soil fertility, greater rainfall, and moderate temperatures of the highland region. However, despite lower yields, protein content was consistently higher in Dasht-grown tubers, which can be attributed to enhanced nitrogen mineralization under warmer climatic conditions.

Quality parameters of tubers

The impact of fertilization on tuber quality traits is presented in Table 8. Key observations include:

- Dry matter content was highest in Vahan under T3, reaching 23.0%
- Starch content was also highest in Vahan under T3 (14.9%)
- Vitamin C content peaked at 23.9 mg 100 g^{-1} in Vahan under T3
- Protein content was higher in Dasht-grown tubers (2.16%, T3), linked to higher temperatures that favor protein biosynthesis.

These findings are consistent with earlier studies reporting that the integration of organic and mineral fertilizers improves both yield and quality parameters of potato tubers under different agro-climatic conditions (Lombardo et al., 2013; Brazinskienė et al., 2014; Gelaye, 2023).

Comparative climatic influence on nutritional indices

The combined effects of fertilization and environmental conditions were evident across nutritional traits.

- The Vahan site favored carbohydrate and vitamin accumulation, as indicated by higher dry matter, starch, and vitamin C levels
- The Dasht site, with its warmer and drier climate, was more conducive to protein synthesis in tubers.

These results underscore the importance of adapting fertilization strategies to local agro-climatic conditions to enhance specific nutritional quality traits in potato production.

Correlation analysis

Pearson's correlation analysis revealed strong positive relationships between yield and several quality parameters (Table 8):

- Tuber yield and dry matter: $r = 0.91$
- Tuber yield and starch content: $r = 0.87$
- Tuber yield and vitamin C content: $r = 0.82$
- Moderate correlation with protein content: $r = 0.68$.

These correlations were computed using *R* statistical software (*cor.test* function) and visualized with the ggpubr package.

The results are consistent with those reported by Brazinskienė et al. (2014), Gelaye (2023), and Lombardo et al. (2013), reinforcing the conclusion that integrated fertilization strategies have a positive and interrelated effect on both potato yield and tuber quality under diverse environmental conditions.

CONCLUSION

The results of this study clearly demonstrate that both the yield and nutritional quality of potato tubers are significantly influenced by fertilization strategies and agro-climatic conditions.

The combined application of mineral fertilizers (N150P120K120) with 40 t ha^{-1} farmyard manure (T3 treatment) produced the highest yields and superior quality parameters, including increased dry matter, starch, vitamin C, and protein content.

Among the two experimental sites, the mountain chernozem soils of Vahan (Gegharkunik region) provided more favorable conditions for the accumulation of dry matter, starch, and vitamin C, owing to cooler temperatures and higher relative humidity.

In contrast, the warmer and drier conditions of Dasht (Armavir region) promoted higher protein synthesis in potato tubers.

These findings highlight the importance of adapting fertilization regimes to local environmental conditions in order to achieve optimal crop performance. Furthermore, the study revealed strong positive correlations between tuber yield and quality parameters such as dry matter, starch, and vitamin C content, confirming the interconnected nature of productivity and nutritional value.

Given the challenges posed by global warming and increasing climate variability, site-specific fertilization strategies are essential for:

- Enhancing sustainable potato production
- Improving nutrient use efficiency
- And developing potato cultivars with superior nutritional and functional properties.

Practical recommendations

Based on the findings, the following practical recommendations can be made for farmers, agronomists, and decision-makers:

1. Adopt integrated fertilization: Combining mineral fertilizers with farmyard manure (40 t ha^{-1}) ensures optimal nutrient balance, leading to higher yields and improved tuber quality.
2. Adjust fertilization to local conditions:

✓ In highland regions like Vahan, prioritize practices that support carbohydrate and vitamin accumulation, such as balanced mineral nutrition and moisture conservation.

✓ In lowland regions like Dasht, focus on nitrogen management to control protein accumulation and prevent excessive vegetative growth.

3. Implement climate-smart practices: Given the predicted effects of climate change, techniques such as mulching, drip irrigation, and crop rotation should be integrated to mitigate soil moisture loss and maintain stable yields.
4. Use soil and climate monitoring data to guide fertilization schedules and ensure efficient nutrient use, reducing environmental impact and production costs.

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