https://doi.org/10.55925/btagr.26.9101

Performance and Adaptability of Wine Grape Varieties in Bhutanese Agroecological Conditions

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Abstract

Grapes (Vitis vinifera L.) are among the most important temperate fruit crops worldwide, widely used for winemaking, fresh consumption, and processed products such as raisins. In Bhutan, however, grape cultivation remains limited due to heavy monsoonal rainfall and insufficient research. While a few table grape varieties have previously been tested, the cultivation of wine grapes is entirely new. To explore their potential for a niche wine industry, 18 wine grape varieties were introduced in 2018 through a Public–Private Partnership between the Department of Agriculture and Bhutan Wine Company. This study evaluated nine of these varieties across three agroecological zones, Lingmethang (600 masl), Bajo (1200 masl), and Paro (2400 masl) from 2019 to 2024, using a Completely Randomized Design with two replications. Data on fruit and yield traits, including cluster number, cluster weight, cluster dimensions, total soluble solids (TSS), berry size, and yield per vine, were analysed using ANOVA and Tukey's test in SPSS and R. The study found that all varieties contained TSS between 18% and 24%, the optimal range for winemaking, and yields between 2.9 and 4.9 kg per vine, highlighting their potential for commercial production. Significant genotype and location effects, along with strong genotype × environment interactions, were observed. Yield performance was site-specific, with Sauvignon Blanc and Pinot Noir performing best at Bajo, and Malbec and Cabernet cultivars excelling at Paro. Overall, all varieties produced superior yields and fruit quality at Paro, which is characterized by a warm climate with lower rainfall compared with the hot, wet conditions of Lingmethang. These findings confirm the feasibility of wine grape cultivation in Bhutan and highlight site-specific varietal suitability for commercial development. Consequently, all nine evaluated varieties were officially released for cultivation during the 27th Variety Release Committee meeting.

Keywords: *Wine grapes; TSS; Yield per vine; wine making*

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1 Introduction

Grapes (*Vitis vinifera* L.), belonging to the family Vitaceae, are among the most important temperate fruit crops worldwide. In 2024, global grape production reached 28.87 million metric tons (MT), cultivated over approximately 7.1 million hectares (International Organisation of Vine and Wine, 2025; USDA, 2025). Grapes are classified as non-climacteric fruits and therefore must be harvested at full physiological maturity to attain the desired quality for fresh consumption or vinification (Venkitasamy et al., 2019). Of the total global production in 2022, approximately 50% was utilized for winemaking, 42% for fresh table grape consumption, and the remaining 8% processed into dried products such as raisins (Cosme et al., 2024). For wine production, grape berries with high acidity, moderate sugar content, and low pH are particularly valued, as these attributes play a critical role in determining wine quality and stability (Jones et al., 2014). Both yield and fruit quality are strongly influenced by climatic conditions and vineyard management practices (Almeida, 2017).

Although grapes are predominantly cultivated in temperate regions, they are also well adapted to subtropical and tropical agro-climatic zones extending into the warm temperate belt (Ghule et al., 2021). Grapevines perform best under a Mediterranean-type climate characterized by long, warm, dry summers and cool, moist winters. Successful grape production requires two distinct seasonal phases: a growing season with adequate warmth and sunlight to support photosynthesis and sugar accumulation in berries, and a winter dormancy period induced by cooler a temperature that allows vines to rest and prepare for the subsequent growing cycle. Optimal growth generally occurs within a temperature range of 15ºC–40 °C and under annual rainfall of around 900 mm.

In Bhutan, however, grape cultivation remains limited compared to other fruit crops, largely due to agro-ecological constraints. The predominance of heavy monsoonal rainfall across most regions coinciding with the harvest, poses significant challenges to grape production, including increased disease pressure and difficulties in vineyard management. Consequently, national grape production in 2024 was only 4.25 MT, accounting for merely 0.0096% of the country’s total fruit production and ranking the lowest among 31 fruit commodities (National Statistics Bureau, 2025). While a few table grape varieties have been evaluated in the past, the cultivation of wine grapes is relatively new in Bhutan.

Recognizing the potential for developing a niche wine industry, the Bhutan Wine Company, in collaboration with the Department of Agriculture (DoA), introduced 18 wine grape varieties from California in 2018. This initiative marked the beginning of a systematic evaluation of wine grape adaptability under Bhutanese conditions. Since 2019, varietal trials have been established under a Public-Private Partnership (PPP) framework at multiple locations, including the Agriculture Research and Development Sub Center (ARDSC) Lingmethang, Agriculture Research and Development Center (ARDC) Bajo, National Seed Center (NSC) Paro, and the National Center for Organic Agriculture (NCOA) Yusipang, with further expansion to ARDC Samtenling in 2022. In parallel, the Bhutan Wine Company has developed commercial vineyards at Pinsa, Gortshalu, and Norjinthang since 2021, covering a total area of approximately 35 acres.

Until 2025, wine production in Bhutan relied entirely on imported grapes. However, with the launch of the country's first wine produced from locally cultivated grapes, *SER KEM Wine*, by the Bhutan Wine Company in 2024, Bhutan entered a new phase in its viticulture and winemaking history. These ongoing varietal trials therefore represent pioneering efforts to assess the feasibility of grape cultivation and wine production under Bhutan's unique agro-climatic conditions. Systematic evaluation of the adaptability, productivity, and fruit quality of introduced wine grape varieties is essential for identifying cultivars suitable for commercial cultivation and for supporting the sustainable development of a domestic wine industry.

The main objectives of this study were to:

a. Assess the adaptability and performance of wine grape varieties under varying agro-climatic conditions; and
b. Identify the most promising wine grape varieties for commercial production in Bhutan.

2 Materials and methods

2.1 Study area

The evaluation trial was initiated in 2019 at four locations representing distinct agroecological zones of Bhutan: ARDSC Lingmethang (600 m above sea level, masl), NCOA Yusipang (2600 masl), NSC Paro (2400 masl), and ARDC Bajo (1200 masl). These sites were selected to assess the performance and adaptability of wine grape varieties across different agroecological zones. However, from 2023 onwards, the trial at Yusipang was discontinued because the center's mandate as the national organic coordinating center does not permit the spray schedules required for grape production. Consequently, data from Yusipang were excluded from the present study.

Climatic conditions varied markedly among the three locations over the past two decades (National Center for Hydrology and meteorology, 2024). Lingmethang received an annual rainfall ranging from 673 mm to 1,185 mm, with mean maximum temperatures of 20ºC–25 °C and minimum temperatures of 11ºC–15°C (Figure 1). Similarly, Bajo experienced annual rainfall between 400 mm and 900 mm, with maximum temperatures ranging from 24 ºC to 27 °C and minimum temperatures from 13°C to 16 °C (Figure 3). In contrast, Paro, located at a higher altitude, received comparatively lower annual rainfall (300 mm–700 mm) and was characterized by cooler temperatures, with maximum temperature of 19ºC–21 °C and minimum temperatures ranging from 5ºC to 11°C (Figure 2).

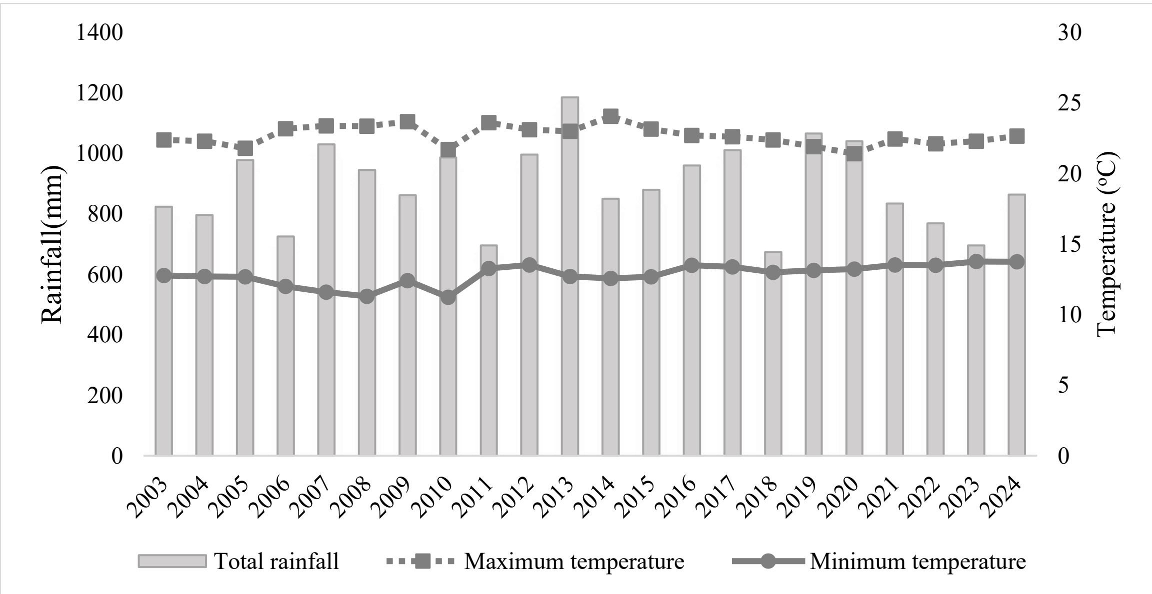

Figure 1. Climate data of Lingmethang

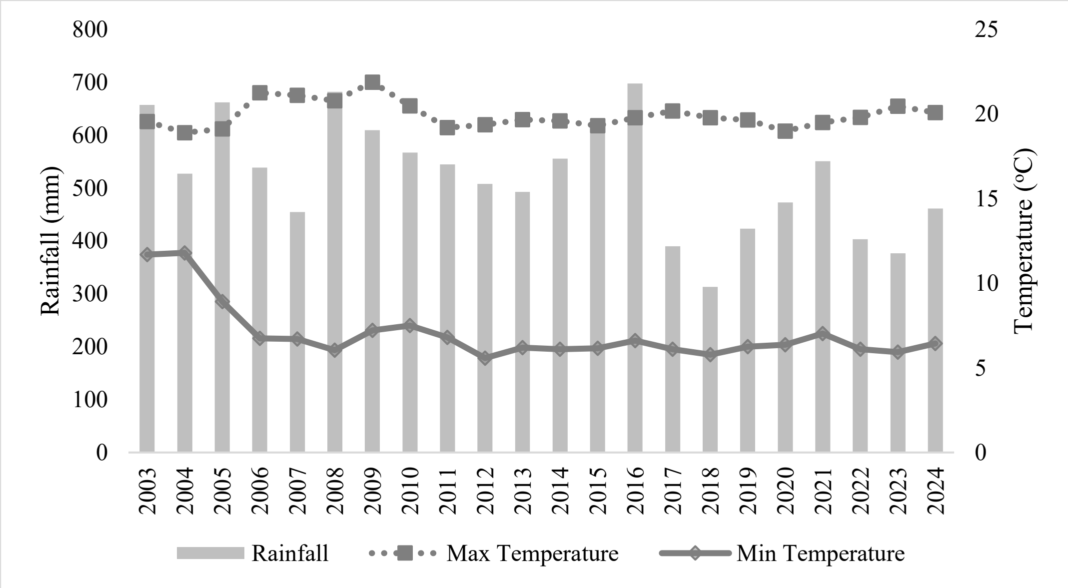

Figure 2. Climate data of Paro

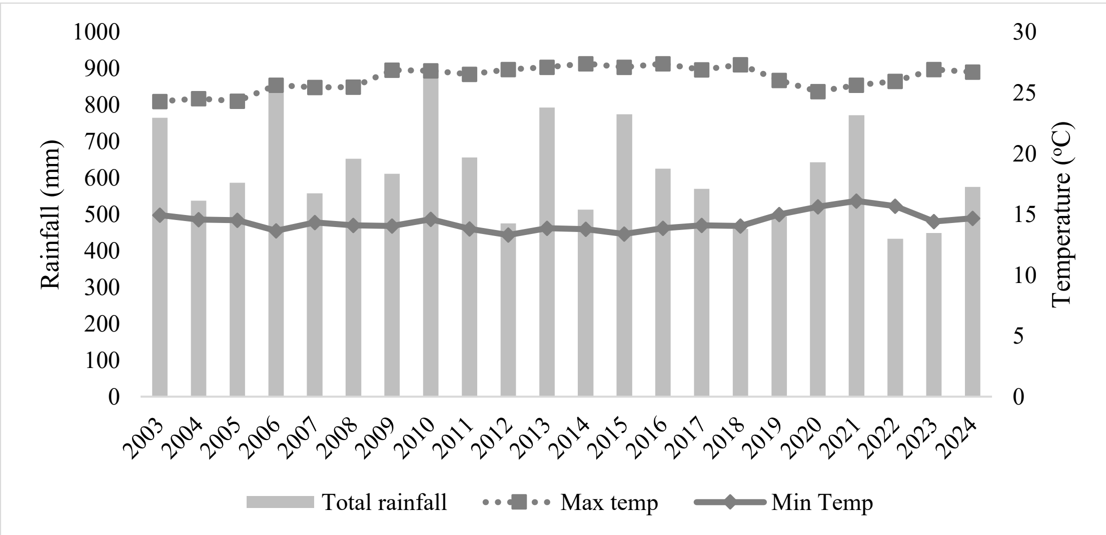

Figure 3. Climate data of Bajo

2.2 Study Design

The study was conducted using nine treatments with three replications in a Completely Randomized Design (CRD), comprising a total of 27 vines at each location. The treatments consisted of nine wine grape varieties which were introduced to Bhutan from California by the Bhutan Wine Company and subsequently shared with the ARDCs and the NSC for evaluation. Among these, three were white grape varieties, while the remaining six were red varieties that develop black coloration upon ripening (Table 1).

Table 1. List of nine varieties and their colour

Treatment	Variety	Berry colour
T1	Cabernet Franc	Red
T2	Cabernet Sauvignon	Red
T3	Chardonnay	White
T4	Malbec	Red
T5	Merlot	Red
T6	Petit Manseng	White
T7	Pinot Noir	Red
T8	Sauvignon Blanc	White
T9	Syrah	Red

Planting pits measuring 40–50 cm in depth were prepared and filled with a mixture of well-decomposed farmyard manure (FYM) and topsoil. A planting mound of 15–20 cm height above ground level was formed, and the seedlings were planted at the center of the mound. To facilitate proper vine growth and canopy development, a Kniffin trellis system was established. Under this system, two primary leaders were trained on either side of the main stem, and the lateral shoots arising from these leaders were tied vertically to the upper wire.

Standard vineyard management practices were followed throughout the study period. Annual pruning was carried out during the dormant season (December–January). Irrigation was supplied through a drip irrigation system to ensure timely and uniform water application, and each vine received 10–15 kg of FYM annually. From fruit set until harvest, a weekly spray schedule was followed using Mancozeb and sulphur @ 2g/lt of water applied alternately to manage downy mildew and powdery mildew. Additionally, insect-proof netting was installed to protect grape clusters from damage by birds and wasps.

2.3 Data collection

For this study, yield and fruit quality data collected over three consecutive years (2022–2024) were used for analysis. Harvesting time varied by location, with wine grapes harvested in July at Lingmethang and Bajo, whereas harvesting at Paro, took place in September. Data on both fruit quality and yield parameters were recorded at all experimental sites.

Fruit quality parameters included berry weight, berry diameter, berry length, total soluble solids (TSS), and number of seeds per berry. Yield parameters comprised number of clusters per vine, cluster weight, cluster length, cluster diameter, number of berries per cluster, and yield per vine. For the assessment of fruit quality, ten berries were randomly selected from harvested clusters of each variety, and their weight, diameter, length, TSS, and seed number were recorded. For yield-related measurements, all harvested clusters per vine were counted, and five clusters were randomly selected from each variety to determine cluster length, cluster diameter, and number of berries per cluster. Total yield per vine was calculated by weighing all clusters harvested from each variety and replication using a digital weighing balance. TSS was measured using a digital refractometer. Berry length and diameter were measured using a vernier caliper, while cluster length and diameter were measured using a 30 cm measuring scale.

2.4 Data Analysis

The average fruit and yield parameters of nine varieties across three locations were analysed using one-way ANOVA, while the interaction effects between location and variety were evaluated through two-way ANOVA. All statistical analyses were carried out in SPSS and R software at a 95% confidence level, and Tukey's HSD test was employed for post hoc comparisons.

3 Results and Discussion

3.1 Overall fruit and yield parameters

3.1.1 Fruit parameters

To assess the overall fruit parameters of nine wine grape varieties, one way ANOVA was conducted. Significant variation was observed among the wine grape varieties for berry length, TSS, and seed content, while differences in berry weight and berry diameter were not statistically significant (Table 2). Berry weight ranged from 1.62 g in Petit Manseng to 2.64 g in Malbec, with a mean value of 2.10 g. Similarly, berry diameter varied from 1.34 cm in Cabernet Sauvignon to 2.16 cm in Petit Manseng with no significant differences among the varieties.

In contrast, berry length differed significantly among varieties ($p < 0.001$). Sauvignon Blanc recorded the longest berries (1.51 cm), followed by Malbec, Chardonnay, and Petit Manseng, while Petit Manseng exhibited the shortest berry length (1.23 cm). These differences in berry length may influence berry morphology and skin-to-pulp ratio, which are important determinants of wine quality attributes such as phenolic extraction and flavor intensity.

TSS content showed highly significant variation among varieties ($p < 0.001$), ranging from 18.85% in Pinot Noir to 23.30% in Petit Manseng, with an overall mean of 20.18%. The significantly higher TSS observed in Petit Manseng indicates superior sugar accumulation potential, which is desirable for producing wines with higher alcohol content or balanced sweetness. Varieties such as Chardonnay and Sauvignon Blanc also exhibited relatively high TSS values with fewer seed content, suggesting good adaptability and favourable ripening behaviour under the experimental conditions. Importantly, all evaluated varieties fall within the widely accepted optimal range for winemaking (18% to 24%), suggesting their suitability for wine making under Bhutanese growing conditions (Yuyuen, Boonkerd and Wanapu, 2015).

Seed content per berry differed significantly among varieties ($p < 0.01$), varying from 1.87 in Chardonnay to 2.70 in Cabernet Franc. Higher seed numbers, as observed in Cabernet Franc and Malbec, may contribute to increased tannin extraction during vinification, potentially influencing wine astringency and structure (Rousserie et al., 2020). Although Malbec produced berries with relatively higher berry weight, it was characterized by lower TSS and higher seed content. These attributes may increase production costs due to the potential need for sugar supplementation during fermentation and additional processing to manage excessive seed-derived tannins. Conversely, lower seed content in Chardonnay may be advantageous for producing wines with softer mouthfeel.

Overall, the results indicate that while berry size traits such as weight and diameter were relatively stable across varieties, berry length, TSS, and seed content exhibited strong varietal influence. The superior TSS in Petit Manseng and favorable berry dimensions in Sauvignon

Blanc and Malbec highlight their potential suitability for quality wine production under the studied agro-climatic conditions.

Table 2. Overall fruit parameters of nine winegrape varieties

Varieties	Berry weight (g)	Berry diameter (cm)	Berry length (cm)	TSS (%)	Seed content (no)
Cabernet Franc	2.02	1.36	1.32 [abc]	19.41	2.70 [a]
Cabernet Sauvignon	1.85	1.34	1.28 [bc]	19.09	2.15 [ab]
Chardonnay	2.01	1.43	1.45 [ab]	21.09	1.87 [b]
Malbec	2.64	1.70	1.46 [ab]	19.58	2.62 [a]
Merlot	2.09	1.44	1.34 [abc]	19.78	2.29 [ab]
Petit Manseng	1.62	2.16	1.23 [c]	23.3	2.26 [ab]
Pinot Noir	2.33	1.47	1.30 [abc]	18.85	2.31 [ab]
Sauvignon Blanc	2.35	1.41	1.51 [a]	20.55	2.24 [ab]
Syrah	1.97	1.53	1.32 [abc]	19.81	2.48 [ab]
Mean	2.10	1.56	1.37	20.18	2.32
StdErr	0.31	0.44	0.06	0.86	0.21
p-Value	ns	ns	***	***	**

**P<5%, ** P<1%, and ***P<0.1%, ns- not significant, StdErr- Standard Error*

3.1.2 Yield parameters

Significant varietal differences were observed for the number of clusters per vine, while cluster morphology traits and yield per vine did not differ significantly among varieties (Table 3). The number of clusters per vine varied significantly among varieties ($p < 0.001$), ranging from 12.08 in Chardonnay to 32.50 in Sauvignon Blanc, with a mean of 23.59 clusters per vine. Sauvignon Blanc recorded the highest cluster number, followed by Cabernet Sauvignon (30.58), but these varieties have lower TSS which need the addition of sugar while making wine. On the other hand, Petit Manseng and Chardonnay have higher TSS but the yield and cluster numbers are comparatively lower.

Cluster weight varied among varieties, ranging from 86.93 g in Petit Manseng to 156.67 g in Malbec, with an overall mean of 109.31 g. Although Malbec exhibited the highest cluster weight, its overall yield remained comparatively lower due to a reduced number of clusters per vine. In contrast, cluster diameter and cluster length did not differ significantly among varieties, with mean values of 6.37 cm and 11.25 cm, respectively. These findings suggest that, under the prevailing experimental conditions, cluster size and shape were relatively stable traits and less responsive to genetic variation among the evaluated wine grape varieties.

The number of berries per cluster ranged from 67.57 in Pinot Noir to 92.42 in Petit Manseng, with a mean of 77.86 berries per cluster. Despite numerical differences, the variation among varieties was non-significant, implying that berry set per cluster was relatively uniform across varieties and possibly more influenced by environmental conditions during flowering and fruit set than by varietal effects.

Yield per vine varied from 1.75 kg in Syrah to 3.69 kg in Sauvignon Blanc, with a mean yield of 2.49 kg per vine. These results differ from previous findings in other regions, where Sauvignon Blanc produced lower yields in Telangana and Syrah exhibited moderate yields in Australia (Dry et al., 2010; Joshi, 2022). The higher yield observed in Sauvignon Blanc can be largely attributed to its significantly higher number of clusters per vine rather than differences in cluster size or berry number. Given that cluster number is a key determinant of yield, higher cluster counts are generally associated with increased productivity (Fataliyev et al., 2025).

Overall, the results suggest that cluster number per vine is the primary yield-determining trait among the evaluated wine grape varieties, while cluster morphology traits showed limited varietal differentiation. The superior cluster production and higher yield potential of Sauvignon Blanc highlight its adaptability and productivity under the studied conditions, whereas varieties such as Chardonnay and Syrah may require improved management practices to enhance reproductive performance.

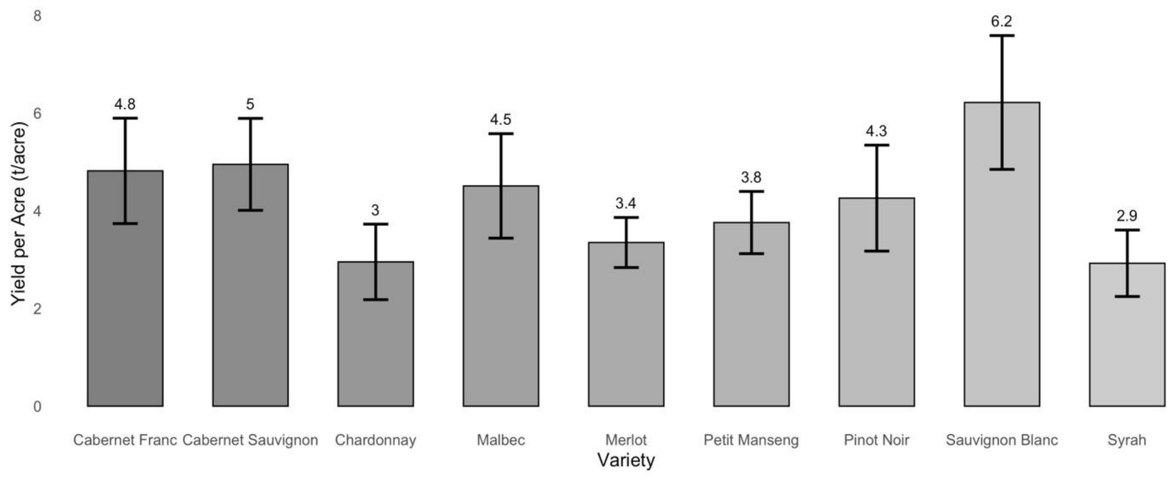

Figure 4. Overall yield/acre of nine winegrape varieties

Table 3. Overall yield parameters of nine winegrape varieties

Varieties	Cluster (no)	Cluster weight (g)	Cluster diameter(cm)	Cluster length (cm)	Berries/cluster (no)	Yield/vine (kg)
Cabernet Franc	23.75 [abc]	99.92	6.11	11.67	72.53	2.85
Cabernet Sauvignon	30.58 [ab]	98.13	6.36	12.03	80.65	2.94
Chardonnay	12.08 [c]	127.39	6.57	12.15	76.08	1.76
Malbec	22.33 [abc]	156.67	7.17	12.41	86.83	2.67
Merlot	25.33 [abc]	91.82	6.06	11.83	76.57	1.99
Petit Manseng	27.42 [abc]	86.93	6.48	10.11	92.42	2.24
Pinot Noir	23.42 [abc]	95.49	5.95	9.29	67.57	2.53
Sauvignon Blanc	32.50 [a]	112.52	6.34	10.23	69.45	3.69
Syrah	14.92 [bc]	114.94	6.33	11.5	78.62	1.75
Mean	23.59	109.31	6.37	11.25	77.86	2.49
StdErr	5.49	24.02	0.8	1.08	14.45	0.79
p-Value	***	ns	ns	ns	ns	ns

**P<5%, ** P<1%, and ***P<0.1%, ns- not significant, StdErr-Standard Error*

3.2 Interactions between locations and varieties

3.2.1 Fruit parameters

The two-way ANOVA showed significant effects of both location and variety on berry weight, diameter, TSS, and seed content ($p < 0.05$), while berry length remained unaffected (Table 4). The significant Location × Treatment interaction highlights that a strong varietal performance varied across agroecological zones.

At Bajo, berries were generally larger, with Pinot Noir recording the highest weight (3.58 g), and Petit Manseng showing the highest TSS (25.45%). TSS was higher across all varieties in Bajo, likely due to warmer temperatures promoting sugar accumulation (Shikhamay & Srinivasulu, 2014). In Lingmethang, berry weights were lower, ranging from 1.17 g to 2.04 g, but Petit Manseng yielded higher TSS of 20.32% followed by 20% in Chardonnay, reflecting adaptability to warm and humid climate (Ting et al., 2025). Similarly, at Paro, berries were small in size, but Petit Manseng once again excelled in sugar content, registering a TSS of 24.12%. This performance is likely linked to its distinct morphological traits, such as small, thick-skinned berries and loosely packed clusters, which allow for extended hang-time on the vine, leading to greater sugar accumulation (Moccio et al., 2023). Seed content was relatively stable across sites, though slightly higher in Paro and Lingmethang. The overall trends confirm that varieties such as Petit Manseng and Chardonnay consistently showed superior

TSS across sites, while Syrah and Malbec performed well in warmer environments, suggesting their potential for site-specific varietal recommendations.

Table 4. Fruit parameters of nine winegrape varieties in three multilocation

Location	Varieties (Treatment)	Berry weight (g)	Berry diameter (cm)	Berry length (cm)	TSS (%)	Seed content (no)
Bajo	Cabernet Franc	3.15^{abc}	1.20	1.30	20.80^{d}	2.50
Bajo	Cabernet Sauvignon	2.55^{cd}	1.12	1.17	21.43^{cd}	2.00
Bajo	Chardonnay	3.15^{abc}	1.35	1.32	22.15^{c}	2.5
Bajo	Malbec	3.38^{ab}	1.40	1.42	21.18^{cd}	2.25
Bajo	Merlot	3.23^{abc}	1.32	1.4	20.88^{d}	2.75
Bajo	Petit Manseng	2.65^{bcd}	4.05	1.32	25.45^{a}	2.25
Bajo	Pinot Noir	3.58^{a}	1.05	1.32	20.40^{d}	2.00
Bajo	Sauvignon Blanc	3.40^{a}	1.33	1.42	23.27^{b}	2.50
Bajo	Syrah	2.30^{d}	1.23	1.32	21.30^{cd}	2.50
Lingmethang	Cabernet Franc	1.47^{de}	1.47^{bc}	1.25^{bc}	17.63^{ab}	2.80^{a}
Lingmethang	Cabernet Sauvignon	1.53^{cde}	1.53^{abc}	1.24^{bc}	16.82^{b}	1.85^{ab}
Lingmethang	Chardonnay	1.38^{de}	1.52^{abc}	1.50^{a}	20.00^{ab}	1.25^{b}
Lingmethang	Malbec	1.97^{ab}	1.98^{ab}	1.27^{abc}	19.74^{ab}	2.80^{a}
Lingmethang	Merlot	1.60^{bcd}	1.60^{abc}	1.19^{bc}	16.78^{b}	2.20^{ab}
Lingmethang	Petit Manseng	1.17^{e}	1.17^{c}	1.09^{c}	20.32^{a}	1.92^{ab}
Lingmethang	Pinot Noir	1.67^{abcd}	1.67^{abc}	1.18^{bc}	16.70^{b}	2.80^{a}
Lingmethang	Sauvignon Blanc	1.90^{abc}	1.40^{c}	1.40^{ab}	19.73^{ab}	2.02^{ab}
Lingmethang	Syrah	2.04^{a}	2.04^{a}	1.35^{ab}	17.50^{ab}	2.12^{ab}
Paro	Cabernet Franc	1.42^{bc}	1.40^{bc}	1.40^{bcd}	19.80^{bc}	2.80^{a}
Paro	Cabernet Sauvignon	1.48^{bc}	1.38^{bc}	1.42^{bcd}	19.05^{bc}	2.60^{a}
Paro	Chardonnay	1.50^{bc}	1.42^{bc}	1.52^{abc}	21.68^{ab}	1.85^{a}
Paro	Malbec	2.58^{a}	1.73^{a}	1.68^{a}	17.82^{c}	2.80^{a}
Paro	Merlot	1.45^{bc}	1.40^{bc}	1.42^{bcd}	21.70^{ab}	1.92^{a}
Paro	Petit Manseng	1.05^{c}	1.25^{c}	1.27^{d}	24.12^{a}	2.60^{a}
Paro	Pinot Noir	1.75^{b}	1.40^{bc}	1.62^{ab}	19.43^{bc}	2.12^{a}
Paro	Sauvignon Blanc	1.75^{b}	1.50^{ab}	1.70^{a}	18.65^{bc}	2.20^{a}
Paro	Syrah	1.57^{bc}	1.32^{bc}	1.30^{cd}	20.65^{bc}	2.80^{a}
	Location (L)	***	0.72	***	***	0.12
	Treatment (TMT)	***	0.7	***	***	0.001
	L X TMT	***	0.2	***	***	0.001

**P<5%, ** P<1%, and ***P<0.1%, ns. not significant*

3.2.2 Yield parameters

The two-way ANOVA revealed significant effects of location and variety on cluster number, cluster weight, cluster length, berries per cluster, yield per vine, and yield per acre ($p < 0.05$), while cluster diameter and berry count were not significantly influenced by treatment alone

(Table 5). Strong location x variety interactions was also observed, indicating that yield performance varied considerably across environments.

At Bajo, Pinot Noir and Sauvignon Blanc recorded the highest yields with 4.12 kg/vine and 3.60 kg/vine, respectively, translating to 6.95–6.05 MT/acre (Figure 3). These values notably exceed those reported by Eleonora et al. (2019), who observed only 1.13 kg/vine in Pinot Noir. The lowest yield was observed in Chardonnay with 0.75 kg/vine. These results suggest that the warm mid-altitude environment favours higher productivity in varieties with compact clusters.

At Lingmethang, overall yields were lower compared with those recorded at Paro and Bajo. Among the evaluated varieties, Cabernet Sauvignon (1.04 kg/vine) and Malbec (1.10 kg/vine) exhibited relatively better performance, whereas Pinot Noir was the least productive, yielding only 0.14 kg/vine. The reduced yields at this location are likely due to the coincidence of harvest with the monsoon season, during which late July rainfall promotes berry rot and associated yield losses. This observation is consistent with the findings of Keller (2010), who reported that elevated temperatures combined with high humidity during fruit maturation can adversely affect grapevine productivity in subtropical environments.

At Paro, yields were highest among locations, particularly in Sauvignon Blanc (6.85 kg/vine; 11.53 MT/acre) and Malbec (5.45 kg/vine; 9.17 MT/acre). Cabernet Sauvignon and Cabernet Franc also produced over 5 kg/vine, demonstrating strong adaptation to cool, high-altitude conditions. The mid-September harvest at this site, coinciding with the end of the monsoon, likely contributed to favourable conditions for cluster development and yield stability (Jones et al., 2005; Leeuwen et al., 2004). In all the locations, the major diseases in all the varieties were powdery mildew and downy mildew, while the main pests were wasp attack and bird damage on the berries.

Overall, the results confirm that site-specific adaptability is crucial for yield optimization. Bajo, a warm mid-altitude, favoured Pinot Noir, Petit Manseng, and Sauvignon Blanc; Paro, a cool highland, supported the highest yields in Sauvignon Blanc, Malbec, and Cabernet cultivars, while a lowland like Lingmethang was less favourable for most varieties, though Malbec and Cabernet Sauvignon showed relative tolerance.

Since all the evaluated varieties exhibited optimum TSS suitable for winemaking together with promising yield potential, all nine were approved and formally released during the 27th Variety Release Committee (VRC) meeting. A limitation of this study was the absence of on-farm data, as the vines had not yet reached the economic bearing stage, and the varieties cultivated on-farm differed from those maintained on-station. This discrepancy prevented direct comparison between on-farm and on-station performance. Future research should therefore prioritize the evaluation of additional varieties under on-farm conditions, and if they demonstrate consistent performance, propose them for release to expand the range of varietal options available for viticulture in Bhutan.

Table 5. Yield parameter of nine winegrape varieties in three multilocation

Location	Varieties (Treatment)	Cluster (no)	Cluster weight (g)	Cluster diameter(cm)	Cluster length (cm)	Berries/cluster (no)	Yield/vine (kg)
Bajo	Cabernet Franc	40.00 ^{ab}	72.20 ^{ab}	4.50 ^{ab}	8.52	49.75	2.88 ^{ab}
Bajo	Cabernet Sauvignon	35.00 ^{abc}	78.35 ^{ab}	4.22 ^{b}	9.2	72.25	2.73 ^{ab}
Bajo	Chardonnay	8.00 ^{c}	91.17 ^{ab}	4.53 ^{ab}	10.1	60.75	0.75 ^{b}
Bajo	Malbec	28.50 ^{abc}	51.5 ^{b}	3.77 ^{b}	8.97	66.5	1.48 ^{ab}
Bajo	Merlot	31.50 ^{abc}	66.1 ^{ab}	4.97 ^{ab}	8.67	61.75	2.08 ^{ab}
Bajo	Petit Manseng	38.25 ^{ab}	82.3 ^{ab}	4.12 ^{b}	8.32	64.5	3.17 ^{ab}
Bajo	Pinot Noir	37.00 ^{ab}	112.2 ^{a}	5.88 ^{a}	10.47	85.25	4.12 ^{a}
Bajo	Sauvignon Blanc	53.00 ^{a}	67.90 ^{ab}	4.72 ^{ab}	9.52	59.25	3.6 ^{a}
Bajo	Syrah	17.00 ^{bc}	92.60 ^{ab}	5.07 ^{ab}	9.72	61.5	1.52 ^{ab}
Lingmethang	Cabernet Franc	7.25 ^{bcd}	82.57 ^{b}	6.07	12.89 ^{ab}	54.08 ^{ab}	0.55 ^{ab}
Lingmethang	Cabernet Sauvignon	18.75 ^{a}	77.53 ^{b}	6.72	11.82 ^{abc}	55.95 ^{ab}	1.04 ^{a}
Lingmethang	Chardonnay	12.00 ^{abcd}	73.25 ^{b}	7.25	11.75 ^{abc}	62.50 ^{ab}	0.85 ^{ab}
Lingmethang	Malbec	12.75 ^{abcd}	147.51 ^{a}	7.2	13.78 ^{a}	73.72 ^{a}	1.10 ^{a}
Lingmethang	Merlot	14.50 ^{abc}	74.61 ^{b}	6.15	10.90 ^{abc}	58.95 ^{ab}	0.86 ^{ab}
Lingmethang	Petit Manseng	16.25 ^{ab}	71.97 ^{b}	6.7	9.85 ^{bcd}	79.75 ^{a}	0.82 ^{ab}
Lingmethang	Pinot Noir	2.75 ^{d}	42.76 ^{b}	5.2	6.67 ^{d}	23.43 ^{b}	0.14 ^{b}
Lingmethang	Sauvignon Blanc	12.00 ^{abcd}	76.90 ^{b}	6.57	8.47 ^{cd}	47.10 ^{ab}	10.62 ^{ab}
Lingmethang	Syrah	3.50 ^{cd}	97.21 ^{ab}	6.78	10.71 ^{abc}	45.60 ^{ab}	0.36 ^{ab}
Paro	Cabernet Franc	24.00 ^{ab}	145.00 ^{b}	7.75	13.57 ^{ab}	113.8	5.15 ^{abc}
Paro	Cabernet Sauvignon	38.00 ^{a}	138.50 ^{b}	8.12	15.05 ^{a}	113.8	5.05 ^{abc}
Paro	Chardonnay	16.25 ^{b}	217.75 ^{ab}	7.92	14.60 ^{a}	105	3.67 ^{bc}
Paro	Malbec	25.75 ^{ab}	271.00 ^{a}	10.53	14.47 ^{ab}	120.3	5.45 ^{ab}
Paro	Merlot	30.00 ^{ab}	134.75 ^{b}	7.05	15.93 ^{a}	109	3.05 ^{bc}
Paro	Petit Manseng	27.75 ^{ab}	106.50 ^{b}	8.6	12.15 ^{ab}	133	2.75 ^{c}
Paro	Pinot Noir	30.50 ^{ab}	131. 50 ^{b}	6.78	10.72 ^{b}	94	3.33 ^{bc}
Paro	Sauvignon Blanc	32.50 ^{a}	192.75 ^{ab}	7.73	12.68 ^{ab}	102	6.85 ^{a}
Paro	Syrah	24.25 ^{ab}	155.00 ^{ab}	7.15	14.05 ^{ab}	128.8	3.35 ^{bc}
	Location (L)	***	***	***	***	***	***

Treatment (TMT)	***	***	0.51	***	0.2	***
L X TMT	***	***	0.02	***	0.26	***

**P<5%, ** P<1%, and ***P<0.1%, ns. not significant*

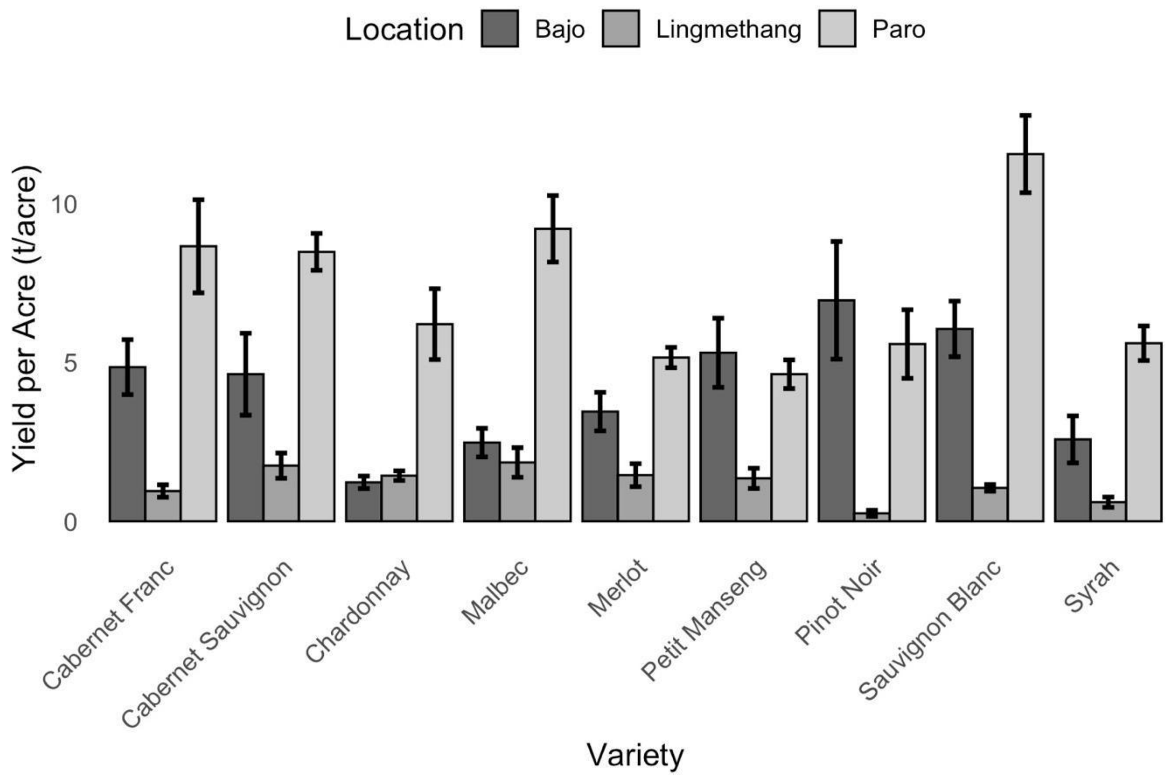

Figure 3. Yield per acre of nine winegrape varieties in three locations

4 Conclusion

Overall, all nine grape varieties exhibited TSS levels within the optimum range for winemaking, coupled with promising yield potential for commercial production in Bhutan. Nevertheless, varietal performance was strongly influenced by location-specific growing conditions, reflecting clear genotype × environment interactions. At Bajo, Pinot Noir, Petit Manseng, and Sauvignon Blanc achieved superior yields, whereas at Paro, Sauvignon Blanc, Malbec, and both Cabernet cultivars (Franc and Sauvignon) recorded the highest productivity. In contrast, Lingmethang appeared less suitable for most varieties, although Malbec and Cabernet Sauvignon demonstrated comparatively better adaptability. These findings underscore the importance of site-specific varietal recommendations, with cool highland regions favouring higher yield potential, mid-altitudes supporting balanced productivity, and lowland environments requiring more careful varietal selection to optimize performance. Future studies should focus on integrating and comparing on-station and on-farm performance data to further validate varietal suitability and support wider adoption by growers.

5 Acknowledgement

We would like to thank the Bhutan Wine Company for providing us with the seedlings and technical guidance for evaluation. A sincere gratitude goes to the Program Director of ARDCs and NSC Paro for the constant guidance and support, and to all the ESPs involved in setting up this trial. We would like to thank all the researchers who were involved in this study.

6 Authors' contribution statement

Pema Yangdon was involved in the implementation of research, data collection, and manuscript preparation. Kinzang Wangmo, Mandira Acharja, Pema Dechen, Kinley Gyeltshen, Thinley Wangdi, and Choki Wangchuk were involved in implementation and data collection, while Thinley Gyeltshen and Kinzang Thinley were involved in data analysis and interpretation of the results.

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